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DEVELOPMENT OF THE WELD-BRAZE JOINING PROCESS

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16. Abstract

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Test results obtained on single-overlap and hat-stiffened panel specimens show that weld-brazed joints were superior in tensile shear, stress rupture, fatigue, and buckling compared with joints fabricated by conventional means. Another attractive feature of the process is that the brazed joint is hermetically sealed by the braze material, which may eliminate many of the sealing problems encountered with riveted or spotwelded structures. The relative ease of fabrication associated with the weld-brazing process may make it cost effective over conventional joining techniques.

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SUMMARY

A new joining process, designated weld-brazing, has been developed which combines resistance spotwelding and brazing. Resistance spotwelding is used to position and aline the parts, as well as to establish a suitable faying-surface gap for brazing. Fabrication is then completed at elevated temperature by capillary flow of the braze alloy into the joint. The process has been used successfully to fabricate Ti-6Al-4V alloy joints by using 3003 aluminum braze alloy and should be applicable to other metal-braze systems.

Test results obtained on single-overlap and hat-stiffened panel specimens show that weld-brazed joints were superior in tensile shear, stress rupture, fatigue, and buckling compared with joints fabricated by conventional means. Another attractive feature of the process is that the brazed joint is hermetically sealed by the braze material, which may eliminate many of the sealing problems encountered with riveted or spotwelded structures. The relative ease of fabrication associated with the weld-brazing process may make it cost effective over conventional joining techniques.

INTRODUCTION

Interest has recently been generated in the combined use of resistance spotwelding and epoxy bonding (weld-bonding) as an effective means of joining aerospace structures. In a study sponsored by the Air Force Materials Laboratory (ref. 1), weld-bonding was used to fabricate aluminum-alloy structures having mechanical properties superior to similar panels fabricated by conventional methods. As a result of this success, an investigation into the applicability of weld-bonding to other material combinations was initiated. A study was undertaken to investigate weld-bonding as a potential joining method in the fabrication of titanium structures. However, since titanium structures are considered for use at temperatures which exceed the capability of current epoxy systems, a higher temperature adhesive was required. The idea of substituting a braze alloy for the adhesive to extend the temperature capabilities was conceived, and the term weld-brazing was selected to describe the joining process. The study reported herein consisted of the fabrication of single-overlap specimens, which were tested at ambient temperature, 450 K, and 560 K (350° and 550° F), and the fabrication of hat-stiffened panels, which were tested in compression at ambient temperature and 560 K (550° F).

The materials used were mill-annealed Ti-6Al-4V alloy sheet and 3003 aluminum braze alloy. In addition to mechanical tests, weld-brazed joints were examined metallurgically to verify adequate flow of the braze and the absence of porosity.

The units for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Measurements and calculations were made in the U.S. Customary Units. Factors relating the two systems are given in reference 2, and those used in the present investigation are presented in the appendix.

PROCESS DEVELOPMENT

In the development of the weld-brazing process, which combines the use of resistance spotwelding with brazing, two primary approaches were investigated. One was designated the prepunched-braze-foil approach (fig. 1) and the other the capillary-flow approach (fig. 2). Both approaches were developed simultaneously, and both proved to be successful joining methods.

In the prepunched-braze-foil approach, the foil was punched (fig. 1) so that the diameter of the holes was approximately 3.18 mm (0.125 in.) larger than the diameter of the intended spotweld nugget. This was done to provide unobstructed weld-nugget formation and to prevent excessive reaction of the parent material with the braze alloy in the vicinity of the spotweld. The braze foil was then placed between titanium strips, which had been chemically cleaned in accordance with procedures outlined in reference 3. The strips were then spotwelded together with the welds made through the holes in the braze. Single-overlap specimens fabricated in this manner showed that expansion of the weld nugget caused the faying-surface gap to be approximately 0.051 mm (0.002 in.) greater than the thickness of the braze foil being used. The braze foil was wider than the overlap in order to have a sufficient volume of braze alloy to adequately fill the gap resulting from welding. Specimens were heated to 950 K (1250° F) in a vacuum of 1.33 mPa (10^{-5} torr) and held for 10 minutes to accomplish the brazing cycle.

In the capillary-flow approach (fig. 2) the titanium strips were first chemically cleaned and then joined by conventional spotwelding techniques. Nugget expansion during welding produced a faying-surface gap which could be varied from 0.051 to 0.102 mm (0.002 to 0.004 in.) by varying the welding parameters listed in table I. After the spotwelding, the braze foil was positioned at the edge of the overlap, and the assembly was heated to the brazing temperature of 950 K (1250° F) in a vacuum of 1.33 mPa (10^{-5} torr) for 10 minutes. Upon melting, the braze alloy was drawn into the gap by capillary action.

The cross section of a weld-brazed joint prepared by use of conventional metallographic polishing and etching techniques is shown in figure 3. Penetration of the braze alloy throughout the joint appears to have occurred without the existence of porosity. A good metallurgical bond exists between the braze and all adjoining titanium surfaces although there is some evidence of the formation of titanium aluminide. However, the formation of the intermetallic to the extent shown was not found to be detrimental. Ultrasonic inspection also verified that a good integral joint had been established.

Both approaches produced satisfactory joints that were hermetically sealed. In the prepunched-foil approach, the positioning of the foil and the welding electrodes, without the aid of precise alinement fixtures, made the process somewhat difficult for application to the fabrication of structural parts. There could be certain applications where the braze would not flow into the faying-surface gap and the prepunched-foil approach would be the better joining method. Weld-brazed joints were fabricated with relative ease by the capillary-flow approach, and it was for this reason that this approach was used to fabricate the test specimens used in the test program.

SPECIMENS AND TEST PROCEDURES

Single-overlap and hat-stiffened panel specimens were fabricated and tested to evaluate the mechanical properties of weld-brazed joints. For all specimens the parent material was 1.27-mm-thick (0.050-in.) annealed Ti-6Al-4V alloy, and the braze material was 0.102-mm-thick (0.004-in.) 3003 aluminum alloy.

Specimens

Single-overlap specimens.- The configurations of the single-overlap specimens are shown in figure 4. Specimens were fabricated by each of three methods: spotwelding, brazing, and weld-brazing. The overlap of approximately 9.53 mm (0.375 in.) on all specimens was selected to insure determination of joint characteristics. The specimen shown on the right side of the figure was used to determine the tensile-shear and stress-rupture properties of the joints. End tabs were spotwelded to the specimens to prevent end failure during testing. The longer specimen shown in the figure was used to determine the fatigue properties of the joints. The single-overlap specimens were fabricated by joining blanks consisting of three half-specimens (fig. 5(a)). The blanks were punched from Ti-6Al-4V sheet material and contained holes for mating, with pins located on the alinement fixture to assure uniformity of the overlap. The weld spacing on the spotwelded-only and weld-brazed specimens was maintained at 25.4 mm (1.0 in.) with the aid of the bakelite alinement fixture shown in figure 5(b). A similar alinement fixture was used for the fabrication of brazed specimens. Shims were placed between the specimen blanks and the fixture to regulate the faying-surface gap during brazing. After the blanks were joined, specimens were cut from the panels, deburred, and cleaned for testing.

Skin-stringer panels.- The basic configuration for the skin-stringer panels is shown in figure 6. All panels were 254 mm (10 in.) long, but the panel width and stringer cross section were varied to give width-to-thickness ratios b_W/t_W of 20, 25, 30, and 40 (fig. 7). The measured dimensions for each panel are listed in table II. Panels were fabricated by riveting only, spotwelding only, and weld-brazing. The riveted panels were fabricated by using 4.06-mm-diameter (0.16-in.) flush-head stainless-steel rivets and a rivet spacing of 12.7 mm (1/2 in.). For comparative purposes, the spacing of the spotwelds in the spotwelded-only and weld-brazed panels was also 12.7 mm (1/2 in.). The weld-brazed panels were fabricated by using welding and brazing parameters outlined previously to obtain a 0.102-mm (0.004-in.) faying-surface gap. A typical metallurgical cross section of a weld-brazed panel is shown in figure 8. The braze alloy, which was placed adjacent to the flange of the stiffener, is shown to have penetrated completely through the joint to form a generous fillet between the inner surface of the stiffener and face sheet. The large quantity of braze in the fillet area is indicative of how well the braze flows by capillary action.

For each value of b_W/t_W studied, the panels were fabricated by each of the following joining methods: riveting, spotwelding, and weld-brazing. In addition, weld-brazed panels with spotweld spacings of 25.4, 50.8, and 127.0 mm (1.0, 2.0, and 5.0 in.) were fabricated with a b_W/t_W of 25 to determine the effect of spotweld spacing on panel strength. The skin-stringer panels were designed as short panels to insure a crippling mode of failure. To prevent end failure of the weld-brazed panel specimens, titanium doublers were spotwelded to the skins of the panels having a b_W/t_W of 20 and 25. The ends of each panel were machined flat, parallel, and perpendicular to the skin in an attempt to introduce uniform loading at the ends of the panels.

Attempts were made to fabricate panel specimens by brazing alone, but numerous difficulties were encountered. It was found difficult to maintain alinement of the hat stringer on the face sheet and to establish a uniform gap for brazing unless elaborate fixtures were used. During the forming, a slight twist developed in the stiffener, which resulted in panel specimens having braze thickness ranging from 0.076 to 0.51 mm (0.003 to 0.020 in.). Therefore, to eliminate the need for fixturing, the stringers were attached to the face sheets by spotwelding at the ends and in the center. The braze alloy was then placed along the edge of the overlap, and fabrication was completed by weld-brazing. This resulted in a weld-brazed specimen having a spotweld spacing of 127.0 mm (5.0 in.) and pointed out some of the advantages of weld-brazing compared with brazing.

Test Procedures

Tensile-shear tests.- The tensile-shear tests of single-overlap specimens were conducted at ambient temperature, 450 K, and 560 K (350° and 550° F) at a constant load rate of 148 N/s (2000 lb/min) by using a 445-kN-capacity (100-kip) hydraulic testing machine. Heating of the specimens tested at elevated temperature was accomplished by using a resistance-wound furnace mounted in the testing machine.

Stress-rupture tests.- Stress-rupture tests were conducted by using single-overlap specimens. The specimens were loaded in conventional creep testing machines, equipped with tube furnaces, to various percentages of the elevated-temperature static tensile-shear strength. The loading was applied shortly after reaching test temperature, and the times to rupture were obtained from elapsed-time indicators that stopped automatically when the specimens ruptured.

Fatigue tests.- Constant-amplitude fatigue tests ($R = 0.05$) were conducted in subresonant-type axial-load fatigue machines (ref. 4). Load was sensed by a weigh-bar in series with the specimen and grips. A wire strain-gage bridge cemented to the weigh-bar supplied a signal to an oscilloscope, which was used to monitor cyclic loading. Operating frequency was 30 hertz.

Compression panel tests.- The skin-stringer structural panels were tested in end compression by using a 1.3-MN-capacity (300-kip) hydraulic testing machine. The edges of the specimens were supported with knife edges positioned 6.35 mm (1/4 in.) from the edge (fig. 9). Relative motion between the upper and lower heads of the testing machine was measured by using linear variable differential transformers (LVDT). For ambient-temperature tests, foil strain gages were attached at the centers of the stiffener and face sheet (fig. 10) and were used to measure local strains. Deviation from linearity was used to represent onset of elastic buckling. Data were recorded every 10 seconds until local instability was achieved and every second from local instability to maximum load. All tests were conducted at a load rate of 890 N/s (12 000 lb/min).

For elevated-temperature tests, the panels were heated by quartz lamps with gold-plated reflectors. Both the skin and the stiffener sides of the panels were heated to the test temperature of 560 K (550° F). A temperature survey on a representative panel indicated that a uniform temperature distribution of ± 3 K ($\pm 5^{\circ}$ F) was achieved over the center 50.8 mm (2 in.) of the panel. The temperature at the ends of the panels ranged from 3 K to 22 K (5° to 40° F) cooler than the center during testing. Panels were heated at a controlled rate of 0.56 K/s (60° F/min), and there was a 5-minute hold between the time the test temperature was reached and the initial application of load. Strains were not measured for any of the panels tested at elevated temperatures; however, load-shortening data were obtained with a dial gage, and deviation from linearity was used to represent onset of elastic buckling.

RESULTS AND DISCUSSION

Single-Overlap Specimens

Tensile shear.- The tensile-shear results obtained at ambient temperature, 450 K, and 560 K (350° and 550° F) for specimens fabricated by spotwelding, brazing, and weld-brazing are presented in table III and figure 11, where the maximum load is plotted against test temperature. The data points are the average of a minimum of three tests with the data spread indicated. The tensile-shear properties of the weld-brazed specimens are shown to be greater than those of the brazed or spotwelded specimens and are approximately equal to the sum of the values shown for the spotwelded and brazed specimens. The strength of the weld-brazed specimens apparently decreases linearly with increasing temperature, and at 560 K (550° F) the specimens were capable of carrying a load which was 85 percent of the value obtained at ambient temperature. The strength of the brazed specimens decreases in a similar fashion, but the spread observed in the data was greater. The increased scatter noted for the brazed specimens was attributed to an inability to maintain a constant faying-surface gap and to the alinement of the parts being joined with the fixturing employed. The weld-brazing process eliminates this difficulty since spotwelding of the parts to be brazed establishes a uniform faying-surface gap by controlled weld-nugget expansion, which in turn maintains alinement of the mating parts during brazing. At a temperature of 560 K (550° F), the average strength of the brazed specimens was equal to approximately 80 percent of the ambient-temperature strength. Although both the weld-brazed and brazed specimens experienced a decrease in strength at 560 K (550° F), the decrease compared with ambient-temperature strength was proportionally less for the weld-brazed specimens. The difference in the percentages noted for the weld-brazed and brazed specimens might be attributed to the fact that the strength of the spotwelds was not temperature dependent.

A typical failure of the single-overlap tensile-shear specimen is shown in figure 12. Most specimens failed by shear of both the spotwelds and aluminum braze, as shown in the photograph. A few specimens failed by shear of the aluminum braze and nugget pull-out of the spotwelds. It can also be seen that the braze penetrated through the overlap and a good bond was formed. The presence of a good bond had been verified by ultrasonic nondestructive evaluation of the specimens prior to testing.

Stress rupture.- The stress-rupture properties at 450 K and 560 K (350° and 550° F) for single-overlap specimens fabricated by spotwelding, brazing, and weld-brazing are shown in figure 13 and are listed in table IV. At 560 K (550° F) for a 500-hour life, the weld-brazed specimens appear capable of carrying approximately twice as much load as the brazed specimens and approximately 10 percent more load than the spot-welded specimens. Although both the weld-brazed and the brazed specimens exhibited substantial decreases in load-carrying ability at 560 K (500° F) compared with 450 K (350° F), the decrease noted for the weld-brazed specimens was proportionally less, probably because of the contribution from the spotwelds. On the basis of these results and those obtained from the tensile-shear tests, it appears possible to tailor the elevated-temperature properties of a weld-brazed joint by varying the number of spotwelds present. Although the strength contribution of the braze decreases with increasing temperature, the strength of the braze should be sufficient to redistribute the stress in the joint so that the stress concentration at the spotwelds is reduced.

Fatigue.- The room-temperature fatigue data obtained from the single-overlap specimens are shown in figure 14 and are listed in table V. Note that the fatigue strengths of the brazed and weld-brazed specimens are approximately equal and that the strengths are approximately 3 times as great as the strength of the spotwelded specimens for a life of 200 000 cycles. Failure of the brazed and weld-brazed specimens occurred in the joint for stress levels resulting in failure in less than about 50 000 cycles, whereas failure of the parent metal occurred for the specimens having a fatigue life greater than about 50 000 cycles. The reason for the change in failure mode was attributed to specimen configuration.

Skin-Stringer Panels

The skin-stringer panels fabricated by weld-brazing, spotwelding, and riveting were tested in axial compression; the data obtained are presented in figures 15 to 18 and are listed in table VI. Typical load-shortening curves are shown in figure 15 for panels fabricated by each of the three joining methods. The initial deviation from linearity represents the onset of local elastic buckling in the skin. Failure of the panel occurs at the indicated maximum load, by crippling of the stiffener and skin as depicted in figure 16.

Maximum strength.- The maximum strength of the skin-stringer panels is shown in figure 17 as a function of panel b_W/t_W. The bars represent the scatter in the data for the values of b_W/t_W tested. The maximum strength of the weld-brazed panels is substantially greater than the spotwelded or riveted panels. A comparison of the maximum strength of the weld-brazed panels with the riveted panels shows that the weld-brazed panels are 1.54 times stronger at a b_W/t_W of 20 and 1.46 times stronger at a b_W/t_W of 40.

Buckling strength.- The buckling strength of the panels is shown in figure 18 as a function of b_W/t_W. Buckling of the weld-brazed panels is shown to occur at a stress which is approximately 1.6 times greater than that of the riveted panels for a b_W/t_W of 40 and 2.25 times greater for a ratio of 20. The increase in load-carrying ability of the weld-brazed panels is attributed to an increased panel stiffness resulting from the continuous bond between the stiffener and face sheet as compared with the discrete attachments inherent with spotwelded and riveted specimens. On the basis of these results, weld-brazing offers increased structural efficiency which should result in substantial weight savings if a structure is designed to carry the same load as a similar structure fabricated by riveting.

Effect of spotweld spacing.- The effect of spotweld spacing on the buckling and maximum strength of the titanium structural panels having b_W/t_W of 25 was investigated at ambient temperature and 560 K (550° F). The test results are presented in figure 19, and the data are listed in table VI. Panels having spotweld spacings of 12.7, 25.4, 50.8, and 127.0 mm (1/2, 1, 2, and 5 in.) were tested at ambient temperature, and panels having spacings of 12.7, 50.8, and 127.0 mm (1/2, 2, and 5 in.) were tested at 560 K (550° F). The data indicate that there is no effect of spotweld spacing on the compressive properties of the panels tested at either temperature. Thus, in the weld-braze process spotweld spacings larger than the rivet spacing required for similar riveted panels can be used to achieve equal properties and reduce fabrication costs.

CONCLUDING REMARKS

A new joining process has been developed which combines the use of resistance spotwelding and brazing and has been designated weld-brazing. The process has been used to join Ti-6Al-4V alloy overlap and skin-stringer panel specimens by using 3003 aluminum braze. Test results obtained from single-overlap shear specimens show that weld-brazed joints are substantially stronger than similarly brazed or spotwelded joints at ambient temperature, 450 K, and 560 K (350° and 550° F). The strength of the weld-brazed joints is approximately equal to the sum of the values obtained from the brazed-only and spotwelded-only specimens. In fatigue, weld-brazed specimens were shown to be capable of carrying 3 times the load for the same fatigue life as specimens which were spotwelded only. Compression tests conducted on skin-stringer panel specimens showed that maximum strength of the weld-brazed panels was 1.46 to 1.54 times higher than that of riveted panels of the same configuration and that the buckling strength of the weld-brazed panels was 1.6 to 2.25 times higher than that of the riveted panels.

On the basis of these results, weld-brazing appears to offer several advantages over joints produced by more conventional means. Weld-brazing offers a substantial increase in structural efficiency, compared with similar structures joined by more conventional techniques. The simplicity of the process compared with brazing or riveting offers economic advantages which may make it cost effective on a production basis. Although the process has only been used to join Ti-6Al-4V alloy by using 3003 aluminum braze, weld-brazing may be adaptable to other material systems where both brazing and spotwelding techniques are viable methods for joining.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., April 26, 1973.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

Conversion factors (ref. 2) for the units used herein are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (a)	SI Unit (b)
Force	kip = 1000 lbf	4.448×10^{3}	newtons (N)
Length	in.	2.54×10^{-2}	meters (m)
Mass	lbm	0.4536	kilograms (kg)
Stress	ksi	6.895×10^{6}	newtons/meter^2 (N/m^2)
Pressure	torr	1.333×10^{2}	pascal (Pa)
Temperature	$^{\circ}F$	$\frac{5}{9}(^{\circ}F + 459.67)$	kelvin (K)

[a]Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

[b]Prefixes to indicate multiples of units are as follows:

Prefix	Multiple	Symbol
milli	10^{-3}	m
kilo	10^{3}	k
mega	10^{6}	M

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TABLE I.- WELDING PARAMETERS FOR 100-kVA THREE-PHASE SPOTWELDER

Parameter	Sheet separation	
	0.051 mm (0.002 in.)	0.102 mm (0.004 in.)
Phase shift, percent	70	70
Weld time, cycles	3	4
Electrode	Class 2, 76.2-mm (3-in.) radius	Class 2, 76.2-mm (3-in.) radius
Electrode force, kN (lbf) . .	4.45 (1000)	4.45 (1000)

TABLE II.- DIMENSIONS OF SKIN-STRINGER PANELS

(a) SI Units

[r_a = 5.1 mm]

Panel	Mass, kg	Length, mm	Width, mm	w, mm	Area, cm^2	b_s, mm	b_w, mm	b_f, mm	b_h, mm	t_s, mm	t_w, mm	Spacing, mm (a)	b_w/t_w
Riveted													
1	0.313	254.0	104.6	91.9	2.781	40.6	26.7	15.2	20.1	1.306	1.293	12.7	20
2	.305	254.0	104.1	91.4	2.710	40.1	26.7	15.5	20.1	1.240	1.285	12.7	20
3	.366	254.0	120.7	108.0	3.252	45.7	33.3	15.5	24.6	1.303	1.318	12.7	25
4	.354	254.0	120.7	108.0	3.148	45.7	33.0	15.5	24.6	1.275	1.247	12.7	25
5	.358	254.0	120.4	107.7	3.181	45.7	33.3	15.5	24.9	1.288	1.288	12.7	25
6	.404	254.0	138.4	125.7	3.594	51.3	38.4	15.5	31.0	1.270	1.270	12.7	30
7	.402	254.0	138.4	125.7	3.574	50.8	38.4	15.5	31.0	1.273	1.275	12.7	30
8	.404	254.0	138.7	126.0	3.594	51.3	38.6	15.2	31.2	1.270	1.278	12.7	30
9	.467	254.0	174.5	161.8	4.155	59.7	51.3	16.0	39.6	1.270	1.295	12.7	40
10	.518	254.0	174.0	161.3	4.613	59.7	51.6	15.7	39.6	1.300	1.308	12.7	40
11	.506	254.0	173.7	161.0	4.497	60.1	51.3	15.7	39.9	1.270	1.298	12.7	40
Spotwelded													
1	0.279	254.0	104.4	91.7	2.477	43.1	25.9	15.2	20.8	1.280	1.280	12.7	20
2	.279	254.0	104.4	91.7	2.484	43.1	25.7	15.2	20.3	1.288	1.267	12.7	20
3	.282	254.0	104.6	91.9	2.503	43.1	25.9	15.2	20.3	1.285	1.295	12.7	20
4	.328	254.0	120.4	107.7	2.916	48.3	31.2	15.2	26.2	1.273	1.283	12.7	25
5	.328	254.0	120.7	108.0	2.916	48.3	31.8	15.2	25.9	1.280	1.285	12.7	25
6	.325	254.0	120.4	107.7	2.890	48.3	32.0	15.5	24.9	1.270	1.262	12.7	25
7	.373	254.0	138.4	125.7	3.316	53.8	37.6	15.7	32.0	1.267	1.255	12.7	30
8	.376	254.0	138.4	125.7	3.336	54.6	37.6	15.5	31.8	1.255	1.267	12.7	30
9	.374	253.7	138.4	125.7	3.323	54.6	37.8	15.5	32.3	1.260	1.278	12.7	30
10	.496	253.7	174.0	161.3	4.413	60.2	49.8	16.0	41.9	1.326	1.318	12.7	40
11	.494	254.0	174.0	161.5	4.387	63.5	51.1	16.0	40.1	1.323	1.300	12.7	40

[a]For riveted panels, spacing between rivets; for spotwelded and weld-brazed panels, spacing between spotwelds.

TABLE II.- DIMENSIONS OF SKIN-STRINGER PANELS – Continued

(a) SI Units – Concluded

[r_a = 5.1 mm]

Panel	Mass, kg	Length, mm	Width, mm	w, mm	Area, cm^2	b_s, mm	b_w, mm	b_f, mm	b_h, mm	t_s, mm	t_w, mm	Spacing, mm (a)	b_w/t_w
Weld-brazed													
1	0.282	254.0	104.1	91.4	2.510	43.2	26.2	15.2	20.6	1.278	1.285	12.7	20
2	.285	254.0	104.6	91.9	2.536	43.2	26.2	16.0	20.8	1.306	1.273	12.7	20
3	.288	254.0	104.4	91.7	2.568	43.2	25.9	14.7	20.6	1.306	1.328	12.7	20
4	.289	254.0	104.6	91.9	2.568	39.1	26.9	15.5	20.8	1.283	1.313	127.0	20
5	.283	254.0	104.1	91.4	2.516	38.1	26.7	15.2	20.1	1.275	1.273	127.0	20
6	.284	254.0	104.6	91.9	2.523	41.9	26.7	15.2	20.8	1.257	1.290	127.0	20
7	.330	254.0	120.7	108.0	2.936	48.3	31.5	15.7	25.4	1.288	1.270	12.7	20
8	.332	254.0	120.7	108.0	2.955	48.3	31.5	16.0	25.9	1.283	1.300	12.7	25
9	.333	253.7	120.4	107.7	2.961	48.3	32.0	16.0	25.4	1.298	1.300	12.7	25
10	.332	253.5	120.9	108.2	2.955	48.3	32.8	15.0	27.9	1.292	1.267	12.7	25
11	.339	253.7	120.9	108.2	3.013	46.2	33.0	14.7	24.9	1.288	1.334	25.4	25
12	.331	254.0	120.9	108.2	2.942	47.8	33.0	14.7	25.4	1.298	1.260	25.4	25
13	.337	254.0	120.7	108.0	3.000	47.8	33.0	14.7	25.9	1.278	1.321	25.4	25
14	.335	254.0	120.7	108.0	2.974	47.8	32.3	15.0	24.9	1.290	1.295	50.8	25
15	.330	254.0	120.4	107.7	2.929	47.8	33.0	14.7	24.9	1.278	1.265	50.8	25
16	.337	253.7	120.7	108.0	2.994	47.8	33.0	14.7	25.4	1.300	1.303	50.8	25
17	.327	253.5	120.9	108.2	2.903	48.3	32.3	15.5	25.1	1.252	1.270	50.8	25
18	.337	254.0	120.7	108.0	3.000	43.4	33.0	15.7	25.9	1.285	1.293	127.0	25
19	.339	254.0	120.7	108.0	3.013	43.9	33.0	15.7	25.9	1.283	1.313	127.0	25
20	.331	254.0	120.4	107.7	2.942	43.9	33.3	15.5	25.7	1.290	1.270	127.0	25
21	.322	253.5	120.9	108.2	2.865	48.5	32.8	15.2	26.7	1.242	1.255	127.0	25
22	.383	254.0	138.4	125.7	3.400	55.9	38.1	15.7	31.8	1.264	1.295	12.7	30
23	.380	254.0	138.4	125.7	3.381	55.6	37.8	15.2	32.5	1.288	1.265	12.7	30
24	.384	254.0	138.2	125.5	3.413	55.1	38.1	16.0	31.5	1.290	1.288	12.7	30
25	.382	254.0	138.4	125.7	3.400	51.3	38.6	15.2	32.0	1.273	1.270	127.0	30
26	.385	254.0	138.4	125.7	3.426	52.8	38.6	15.2	32.0	1.280	1.283	127.0	30
27	.380	254.0	138.4	125.7	3.381	50.8	38.9	15.2	31.5	1.275	1.270	127.0	30
28	.498	254.0	173.7	161.0	4.426	64.8	50.5	15.7	40.1	1.306	1.311	12.7	40
29	.499	254.0	174.0	161.3	4.432	64.8	50.5	15.2	41.7	1.341	1.298	12.7	40
30	.488	254.0	173.7	161.0	4.336	64.8	50.3	15.7	41.1	1.293	1.300	12.7	40
31	.493	254.0	173.7	161.0	4.381	62.0	51.6	16.0	41.4	1.260	1.303	127.0	40
32	.493	254.0	173.7	161.0	4.381	61.5	51.3	15.2	40.4	1.280	1.300	127.0	40
33	.490	254.0	173.7	161.0	4.355	60.5	51.6	15.2	40.1	1.280	1.300	127.0	40

[a]For riveted panels, spacing between rivets; for spotwelded and weld-brazed panels, spacing between spotwelds.

TABLE II.- DIMENSIONS OF SKIN-STRINGER PANELS – Continued

(b) U.S. Customary Units

[r_a = 0.20 in.]

Panel	Mass, lbm	Length, in.	Width, in.	w, in.	Area, in^2	b_s, in.	b_w, in.	b_f, in.	b_h, in.	t_s, in.	t_w, in.	Spacing, in. (a)	b_w/t_w
Riveted													
1	0.690	10.00	4.12	3.62	0.431	1.60	1.05	0.60	0.79	0.0514	0.0509	1/2	20
2	.672	10.00	4.10	3.60	.420	1.58	1.05	.61	.79	.0488	.0506	1/2	20
3	.806	10.00	4.75	4.25	.504	1.80	1.31	.61	.97	.0513	.0519	1/2	25
4	.780	10.00	4.75	4.25	.488	1.80	1.30	.61	.97	.0502	.0491	1/2	25
5	.789	10.00	4.74	4.24	.493	1.80	1.31	.61	.98	.0507	.0507	1/2	25
6	.891	10.00	5.45	4.95	.557	2.02	1.51	.61	1.22	.0500	.0500	1/2	30
7	.886	10.00	5.45	4.95	.554	2.00	1.51	.61	1.22	.0501	.0502	1/2	30
8	.891	10.00	5.46	4.96	.557	2.02	1.52	.60	1.23	.0500	.0503	1/2	30
9	1.030	10.00	6.87	6.37	.644	2.35	2.02	.63	1.56	.0500	.0510	1/2	40
10	1.143	10.00	6.85	6.35	.715	2.35	2.03	.62	1.56	.0512	.0515	1/2	40
11	1.116	10.00	6.84	6.34	.697	2.37	2.02	.62	1.57	.0500	.0511	1/2	40
Spotwelded													
1	0.615	10.00	4.11	3.61	0.384	1.70	1.02	0.60	0.82	0.0504	0.0504	1/2	20
2	.616	10.00	4.11	3.61	.385	1.70	1.01	.60	.80	.0507	.0499	1/2	20
3	.621	10.00	4.12	3.62	.388	1.70	1.02	.60	.80	.0506	.0510	1/2	20
4	.723	10.00	4.74	4.24	.452	1.90	1.23	.60	1.03	.0501	.0505	1/2	25
5	.724	10.00	4.75	4.25	.452	1.90	1.25	.60	1.02	.0504	.0506	1/2	25
6	.717	10.00	4.74	4.24	.448	1.90	1.26	.61	.98	.0500	.0497	1/2	25
7	.823	10.00	5.45	4.95	.514	2.12	1.48	.62	1.26	.0499	.0494	1/2	30
8	.828	10.00	5.45	4.95	.517	2.15	1.48	.61	1.25	.0494	.0499	1/2	30
9	.824	9.99	5.45	4.95	.515	2.15	1.49	.61	1.27	.0496	.0503	1/2	30
10	1.094	9.99	6.85	6.35	.684	2.37	1.96	.63	1.65	.0522	.0519	1/2	40
11	1.088	10.00	6.85	6.36	.680	2.50	2.01	.63	1.58	.0521	.0512	1/2	40

[a]For riveted panels, spacing between rivets; for spotwelded and weld-brazed panels, spacing between spotwelds.

TABLE II.- DIMENSIONS OF SKIN-STRINGER PANELS – Concluded

(b) U.S. Customary Units – Concluded

$[r_a = 0.20 \text{ in.}]$

Panel	Mass, lbm	Length, in.	Width, in.	w, in.	Area, in^2	b_s, in.	b_w, in.	b_f, in.	b_h, in.	t_s, in.	t_w, in.	Spacing, in. (a)	b_w/t_w
Weld-brazed													
1	0.622	10.00	4.10	3.60	0.389	1.70	1.03	0.60	0.81	0.0503	0.0506	1/2	20
2	.629	10.00	4.12	3.62	.393	1.70	1.03	.63	.82	.0514	.0501	1/2	20
3	.636	10.00	4.11	3.61	.398	1.70	1.02	.58	.81	.0514	.0523	1/2	20
4	.637	10.00	4.12	3.62	.398	1.54	1.06	.61	.82	.0505	.0517	5	20
5	.624	10.00	4.10	3.60	.390	1.50	1.05	.60	.79	.0502	.0501	5	20
6	.625	10.00	4.12	3.62	.391	1.65	1.05	.60	.82	.0495	.0508	5	20
7	.728	10.00	4.75	4.25	.455	1.90	1.24	.62	1.00	.0507	.0500	1/2	25
8	.733	10.00	4.75	4.25	.458	1.90	1.24	.63	1.02	.0505	.0512	1/2	25
9	.735	9.99	4.74	4.24	.459	1.90	1.26	.63	1.00	.0511	.0512	1/2	25
10	.732	9.98	4.76	4.26	.458	1.90	1.29	.59	1.10	.0509	.0499	1/2	25
11	.747	9.99	4.76	4.26	.467	1.82	1.30	.58	.98	.0507	.0525	1	25
12	.730	10.00	4.76	4.26	.456	1.88	1.30	.58	1.00	.0511	.0496	1	25
13	.744	10.00	4.75	4.25	.465	1.88	1.30	.58	1.02	.0503	.0520	1	25
14	.738	10.00	4.75	4.25	.461	1.88	1.27	.59	.98	.0508	.0510	2	25
15	.727	10.00	4.74	4.24	.454	1.88	1.30	.58	.98	.0503	.0498	2	25
16	.743	9.99	4.75	4.25	.464	1.88	1.31	.58	1.00	.0512	.0513	2	25
17	.720	9.98	4.76	4.26	.450	1.90	1.27	.61	.99	.0493	.0500	2	25
18	.744	10.00	4.75	4.25	.465	1.71	1.30	.62	1.02	.0506	.0509	5	25
19	.748	10.00	4.75	4.25	.467	1.73	1.30	.62	1.02	.0505	.0517	5	25
20	.730	10.00	4.74	4.24	.456	1.73	1.31	.61	1.01	.0508	.0500	5	25
21	.710	9.98	4.76	4.26	.444	1.91	1.29	.60	1.05	.0489	.0490	5	25
22	.844	10.00	5.45	4.95	.527	2.20	1.50	.62	1.25	.0498	.0510	1/2	30
23	.838	10.00	5.45	4.95	.524	2.19	1.49	.60	1.28	.0507	.0498	1/2	30
24	.846	10.00	5.44	4.94	.529	2.17	1.50	.63	1.24	.0508	.0507	1/2	30
25	.843	10.00	5.45	4.95	.527	2.02	1.52	.60	1.26	.0501	.0500	5	30
26	.849	10.00	5.45	4.95	.531	2.08	1.52	.60	1.26	.0504	.0505	5	30
27	.839	10.00	5.45	4.95	.524	2.00	1.53	.60	1.24	.0502	.0500	5	30
28	1.098	10.00	6.84	6.34	.686	2.55	1.99	.62	1.58	.0514	.0516	1/2	40
29	1.099	10.00	6.85	6.35	.687	2.55	1.99	.60	1.64	.0528	.0511	1/2	40
30	1.076	10.00	6.84	6.34	.672	2.55	1.98	.62	1.62	.0509	.0512	1/2	40
31	1.087	10.00	6.84	6.34	.679	2.44	2.03	.63	1.63	.0496	.0513	5	40
32	1.087	10.00	6.84	6.34	.679	2.42	2.02	.60	1.59	.0504	.0512	5	40
33	1.080	10.00	6.84	6.34	.675	2.38	2.03	.60	1.58	.0504	.0512	5	40

[a]For riveted panels, spacing between rivets; for spotwelded and weld-brazed panels, spacing between spotwelds.

TABLE III.- SINGLE-OVERLAP TENSILE-SHEAR DATA

Load					
Spotwelded specimen		Brazed specimen		Weld-brazed specimen	
kN	lbf	kN	lbf	kN	lbf
Ambient temperature					
18.3267	4120.0	39.4112	8 860.0	58.1827	13 080.0
18.6380	4190.0	39.9005	8 970.0	57.1596	12 850.0
18.2822	4110.0	39.9450	8 980.0	54.8466	12 330.0
17.9486	4035.0	45.0160	10 120.0		
18.5491	4170.0	41.5464	9 340.0		
18.1932	4090.0	41.3684	9 300.0		
450 K (350° F)					
18.6380	4190.0	29.5362	6 640.0	48.9304	11 000.0
21.1068	4745.0	41.1016	9 240.0	50.8432	11 430.0
18.0598	4060.0	29.7141	6 680.0	49.7311	11 180.0
		42.5250	9 560.0		
		45.2829	10 180.0		
560 K (550° F)					
19.4610	4375.0	27.0452	6 080.0	45.2829	10 180.0
19.2163	4320.0	31.7158	7 130.0	42.1691	9 480.0
18.3489	4125.0	29.3138	6 590.0	47.8628	10 760.0
		32.9613	7 410.0	45.3718	10 200.0

TABLE IV.- SINGLE-OVERLAP STRESS-RUPTURE DATA

Temperature		Load		Time to rupture, hr
K	°F	kN	lbf	
Spotwelded				
560	550	18.0569	4059.4	[a]1658.0
560	550	17.1065	3845.7	[a]1656.0
Brazed				
560	550	18.0874	4066.2	0.5
560	550	15.0728	3388.5	1.6
560	550	9.0437	2033.1	[a]650.0
560	550	6.0291	1355.4	[a]650.0
450	350	25.6031	5755.8	37.7
450	350	21.3359	4796.5	[a]672.3
450	350	17.0687	3837.2	[a]689.0
Weld-brazed				
560	550	36.0840	8112.0	0.1
560	550	27.0630	6084.0	1.4
560	550	27.0630	6084.0	2.3
560	550	22.5525	5070.0	28.0
560	550	20.2972	4563.0	258.8
560	550	18.0420	4056.0	610.9
560	550	13.5315	3042.0	[a]1581.9
450	350	39.8561	8960.0	39.7
450	350	29.8920	6720.0	[a]809.0

[a]Test terminated prior to rupture.

TABLE V.- SINGLE-OVERLAP FATIGUE DATA

Maximum load		Mean load		Minimum load		Life, cycles
kN	lbf	kN	lbf	kN	lbf	
Spotwelded						
13.3445	3000.0	7.0059	1575.0	0.6672	150.0	1 000
8.8964	2000.0	4.6706	1050.0	.4448	100.0	4 530
5.4980	1236.0	2.8869	649.0	.2758	62.0	21 000
3.6653	824.0	1.9239	432.5	.1824	41.0	50 000
2.6689	600.0	1.4012	315.0	.1334	30.0	206 000
Brazed						
22.2411	5000.0	11.6766	2625.0	1.1121	250.0	12 330
17.7929	4000.0	9.3413	2100.0	.8896	200.0	35 880
12.7931	2876.0	6.7168	1510.0	.6405	144.0	44 000
8.5272	1917.0	4.4794	1007.0	.4270	96.0	238 000
Weld-brazed						
32.0272	7200.0	16.8143	3780.0	1.6014	360.0	2 000
28.3663	6377.0	15.6044	3508.0	2.8380	638.0	5 000
22.2411	5000.0	11.6766	2625.0	1.1121	250.0	10 000
17.0367	3830.0	8.9454	2011.0	.8585	193.0	21 000
17.0367	3830.0	8.9454	2011.0	.8585	193.0	26 000
13.3445	3000.0	7.0059	1575.0	.6672	150.0	70 000
11.3474	2551.0	5.9606	1340.0	.5694	128.0	120 000
11.3474	2551.0	5.9606	1340.0	.5694	128.0	133 000
11.1206	2500.0	5.8405	1313.0	.5560	125.0	98 000
8.8964	2000.0	4.6706	1050.0	.4448	100.0	242 000
8.8964	2000.0	4.6706	1050.0	.4448	100.0	257 000

TABLE VI.- SKIN-STRINGER COMPRESSION PANEL DATA

(a) Ambient-temperature tests

Panel	b_w/t_w	Maximum load		Maximum stress		Buckling strength (a)		Buckling strength (b)	
		MN	kips	MN/m[2]	ksi	MN/m[2]	ksi	MN/m[2]	ksi
Riveted									
1	20	0.1619	36.4	583.3	84.6	407.5	59.1	433.0	62.8
2	20	.1534	34.5	566.8	82.2	379.9	55.1	394.4	57.2
3	25	.1708	38.4	526.8	76.4	412.3	59.8	403.4	58.2
4	25	.1588	35.7	504.7	73.2	295.8	42.9	329.6	47.8
5	25	.1650	37.1	519.2	75.3	351.6	51.0	368.2	53.4
6	30	.1632	36.7	454.4	65.9	273.0	39.6	319.2	46.3
7	30	.1650	37.1	462.0	67.0	315.1	45.7	336.5	48.8
8	30	.1615	36.3	448.9	65.1	233.1	33.8	272.4	39.5
9	40	.1686	37.9	406.1	58.9	241.3	35.0	273.0	39.6
10	40	.1775	39.9	384.7	55.8	209.6	30.4	242.0	35.1
11	40	.1713	38.5	380.6	55.2	224.8	32.6	359.9	37.7
Spotwelded									
1	20	0.1833	41.2	739.1	107.2	558.5	81.0	614.3	89.1
2	20	.1908	42.9	767.4	111.3	549.5	79.7	617.8	89.6
3	20	.1850	41.6	739.1	107.2	542.6	78.7	621.9	90.2
4	25	.1971	44.3	676.4	98.1	450.9	65.4	495.8	71.9
5	25	.1904	42.8	653.0	94.7	443.3	64.3	488.2	70.8
6	25	.1815	40.8	627.4	91.0	438.5	63.6	489.5	71.0
7	30	.1882	42.3	566.8	82.2	373.7	54.2	418.5	60.7
8	30	.1882	42.3	564.0	81.8	347.5	50.4	406.8	59.0
9	30	.1864	41.9	561.3	81.4	342.7	49.7	375.1	54.4
10	40	.1988	44.7	450.2	65.3	266.8	38.7	317.2	46.0
11	40	.1890	42.5	431.6	62.6	308.9	44.8	314.4	45.6

[a]Deviation from linearity of strain-gage output.

[b]Deviation from linearity of load-shortening curve.

TABLE VI.- SKIN-STRINGER COMPRESSION PANEL DATA – Continued

(a) Ambient-temperature tests – Concluded

Panel	b_w/t_w	Maximum load		Maximum stress		Buckling strength (a)		Buckling strength (b)	
		MN	kips	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi
Weld-brazed									
1	20	0.2175	48.9	866.0	125.6	866.0	125.6	(c)	(c)
2	20	.2277	51.2	897.7	130.2	897.0	130.1	(c)	(c)
3	20	.2286	51.4	890.8	129.2	890.1	129.1	(c)	(c)
4	20	.2189	49.2	852.2	123.6	852.2	123.6	(c)	(c)
5	20	.2291	51.5	910.1	132.0	902.6	130.9	(c)	(c)
6	20	.2313	52.0	917.0	133.0	899.8	130.5	(c)	(c)
7	25	.2322	52.2	790.9	114.7	774.3	112.3	(c)	(c)
8	25	.2420	54.4	819.1	118.8	817.1	118.5	(c)	(c)
9	25	.2589	58.2	873.6	126.7	873.6	126.7	(c)	(c)
11	25	.2558	57.5	848.1	123.0	837.1	121.4	(c)	(c)
12	25	.2482	55.8	843.3	122.3	839.8	121.8	(c)	(c)
13	25	.2607	58.6	868.8	126.0	836.4	121.3	(c)	(c)
14	25	.2571	57.8	863.9	125.3	841.2	122.0	(c)	(c)
15	25	.2518	56.6	859.1	124.6	855.7	124.1	(c)	(c)
16	25	.2589	58.2	864.6	125.4	853.6	123.8	(c)	(c)
18	25	.2424	54.5	808.1	117.2	796.4	115.5	(c)	(c)
19	25	.2424	54.5	804.6	116.7	717.8	104.1	(c)	(c)
20	25	.2531	56.9	860.5	124.8	852.2	123.6	(c)	(c)
22	30	.2318	52.1	681.2	98.8	638.5	92.6	630.9	91.5
23	30	.2290	51.5	677.1	98.2	599.9	87.0	608.1	88.2
24	30	.2429	54.6	710.9	103.1	623.3	90.4	628.1	91.1
25	30	.2295	51.6	674.3	97.8	639.2	92.7	591.6	85.8
26	30	.2447	55.0	713.6	103.5	598.5	86.8	627.4	91.0
27	30	.2384	53.6	704.7	102.2	589.5	85.5	585.4	84.9
28	40	.2362	53.1	533.7	77.4	465.4	67.5	373.7	54.2
29	40	.2433	54.7	548.8	79.6	380.6	55.2	371.6	53.9
30	40	.2318	52.1	535.1	77.6	381.3	55.3	364.1	52.8
31	40	.2055	46.2	468.9	68.0	367.5	53.3	344.8	50.0
32	40	.2362	53.1	538.5	78.1	493.7	71.6	365.4	53.0
33	40	.2384	53.6	547.5	79.4	464.7	67.4	352.3	51.1

[a]Deviation from linearity of strain-gage output.

[b]Deviation from linearity of load-shortening curve.

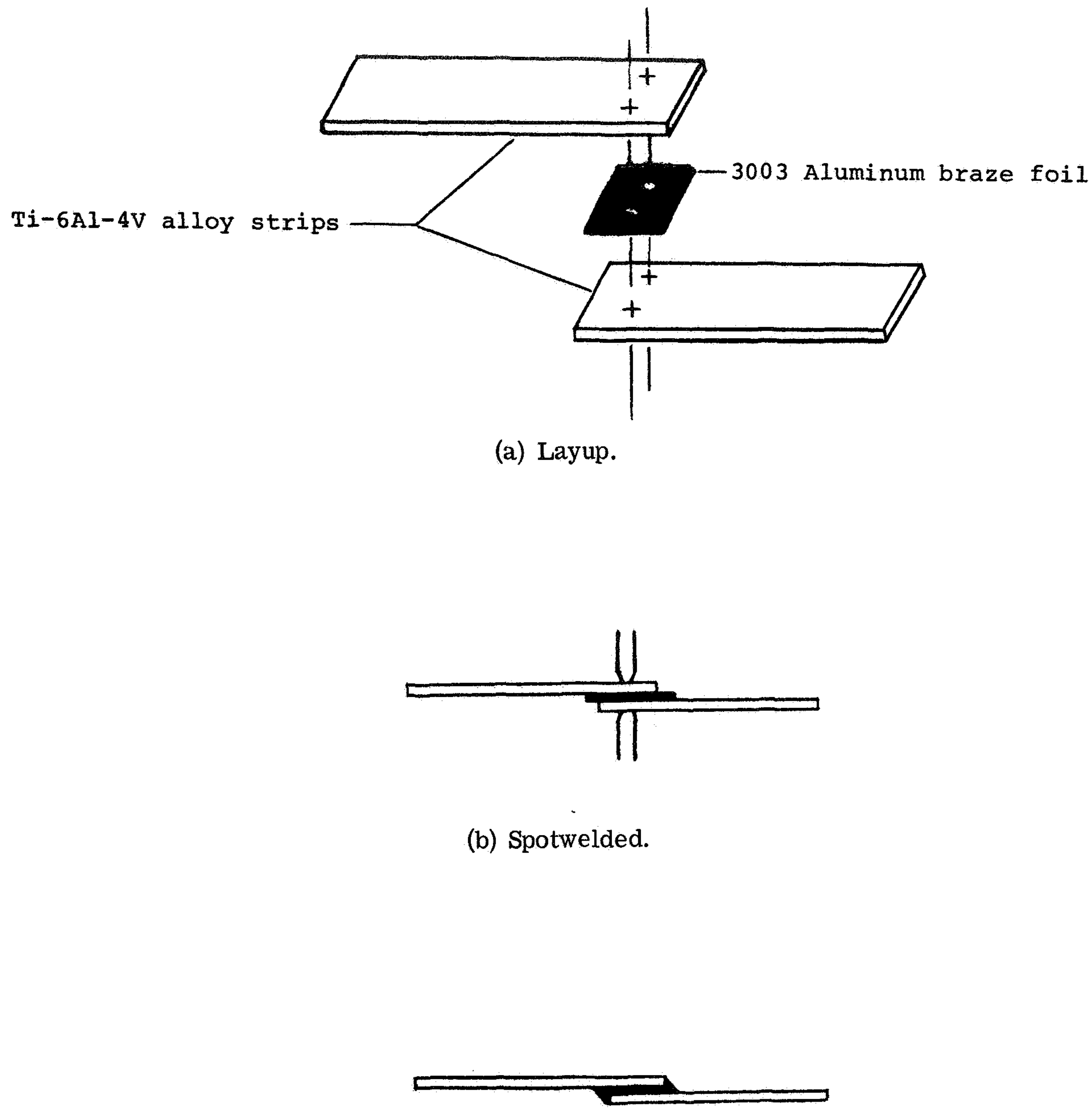
[c]Deviation from linearity coincided with maximum load.

TABLE VI.- SKIN-STRINGER COMPRESSION PANEL DATA – Concluded

(b) Elevated-temperature tests at 560 K (550° F)

[Weld-brazed specimens]

Panel	b_w/t_w	Maximum load		Maximum stress	
		MN	kips	MN/m^2	ksi
10	25	0.1877	42.2	636.4	92.3
17	25	.1837	41.3	633.0	91.8
21	25	.1797	40.4	628.1	91.1

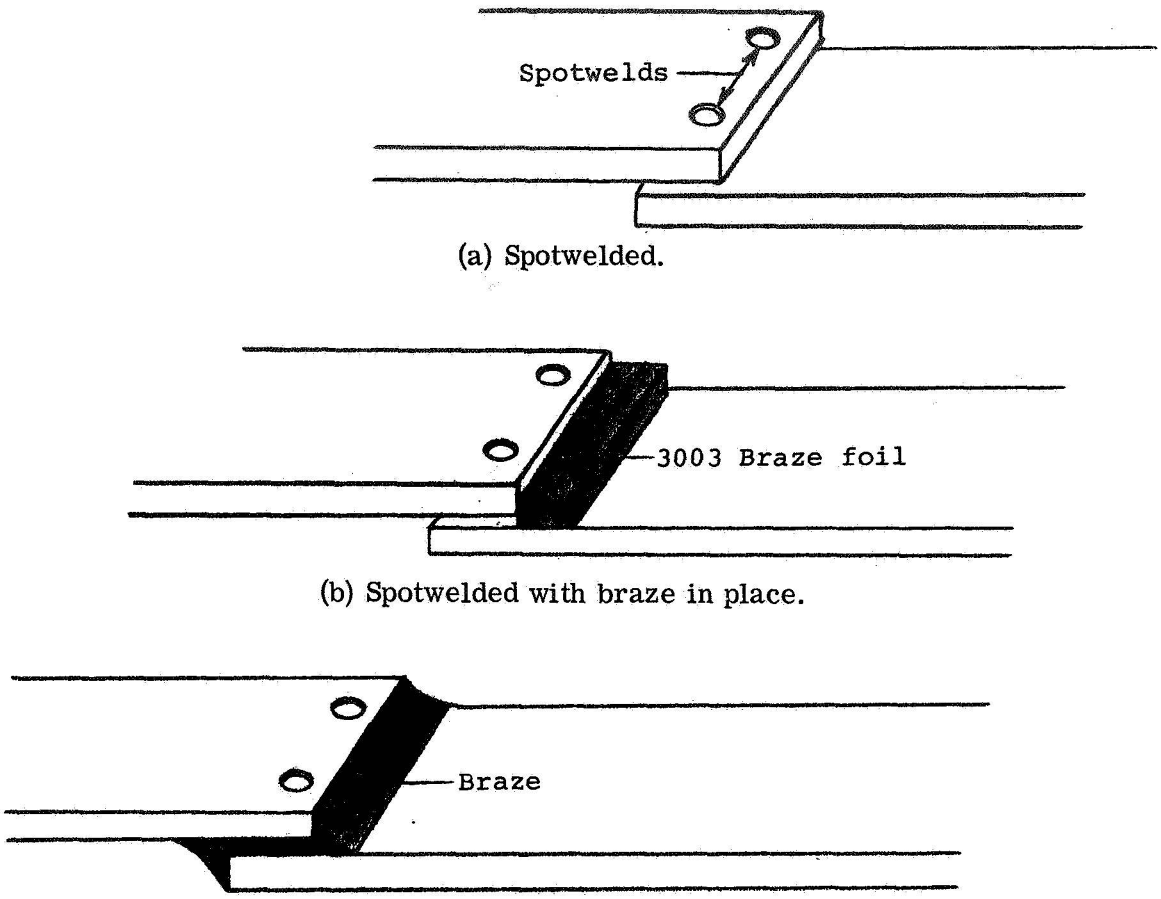


(a) Layup.

(b) Spotwelded.

(c) Weld-brazed.

Figure 1.- Weld-brazing with prepunched foil.



(a) Spotwelded.

(b) Spotwelded with braze in place.

(c) Weld-brazed.

Figure 2.- Weld-brazing with capillary flow.

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Figure 3.- Weld-nugget—braze interface.

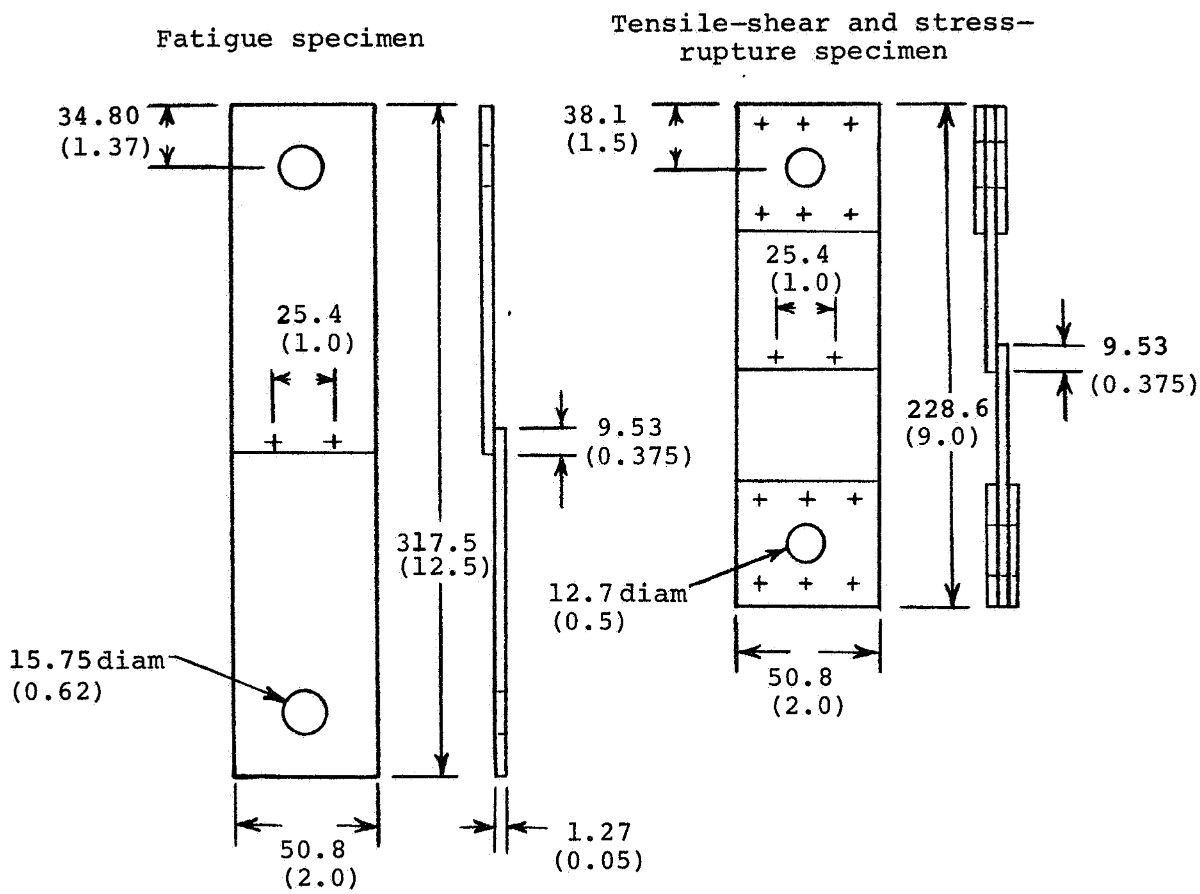
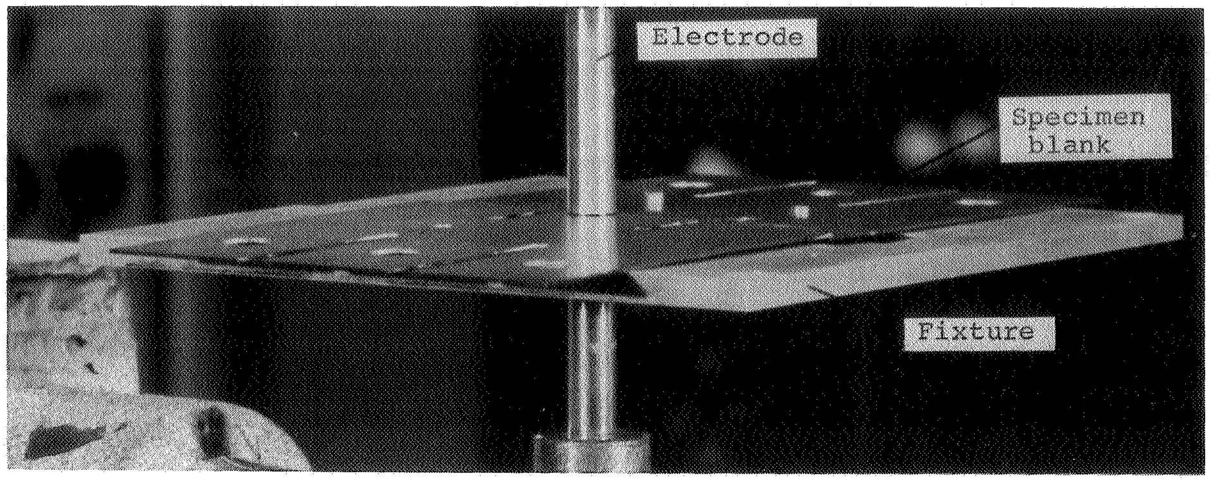
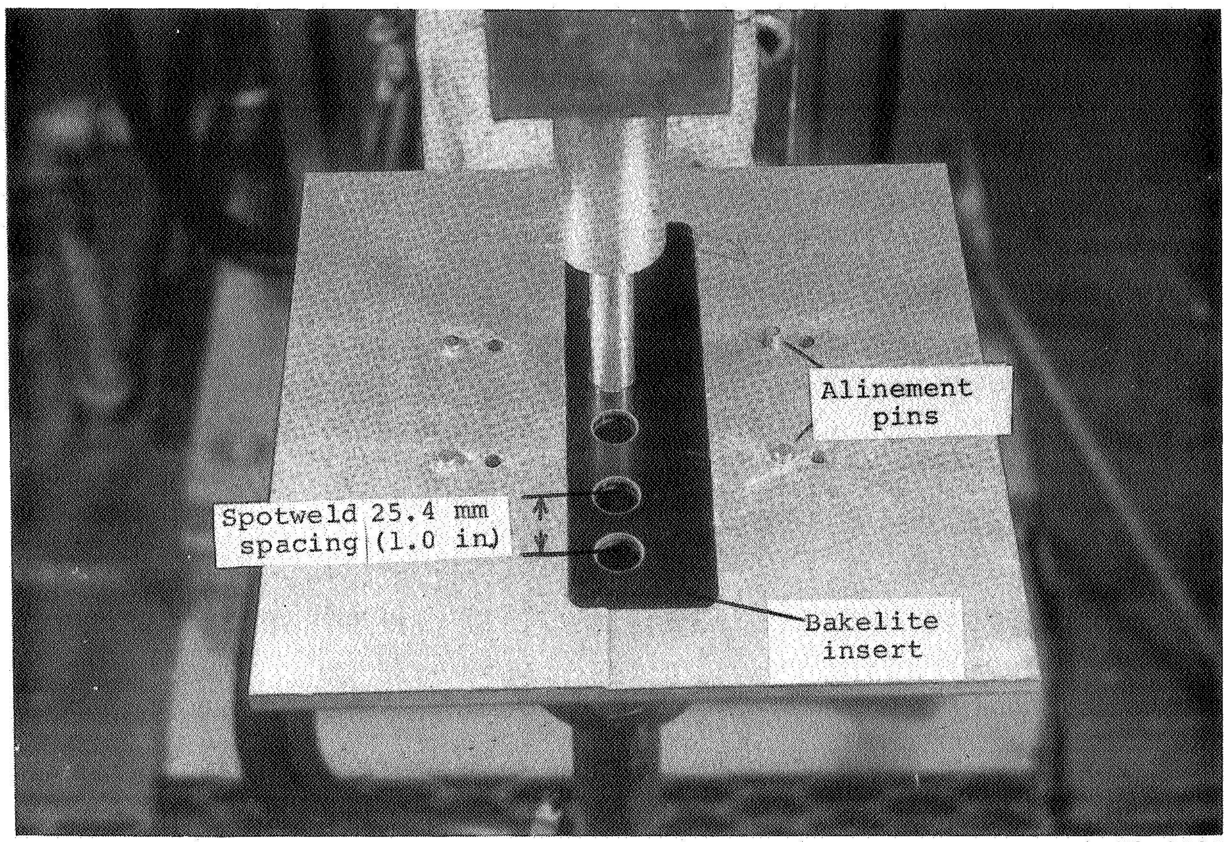


Figure 4.- Single-overlap specimens. Dimensions are given in millimeters (inches).



(a) Spotweld setup.



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(b) Alinement fixture.

Figure 5.- Spotwelding setup and alinement fixture for fabricating single-overlap specimens.

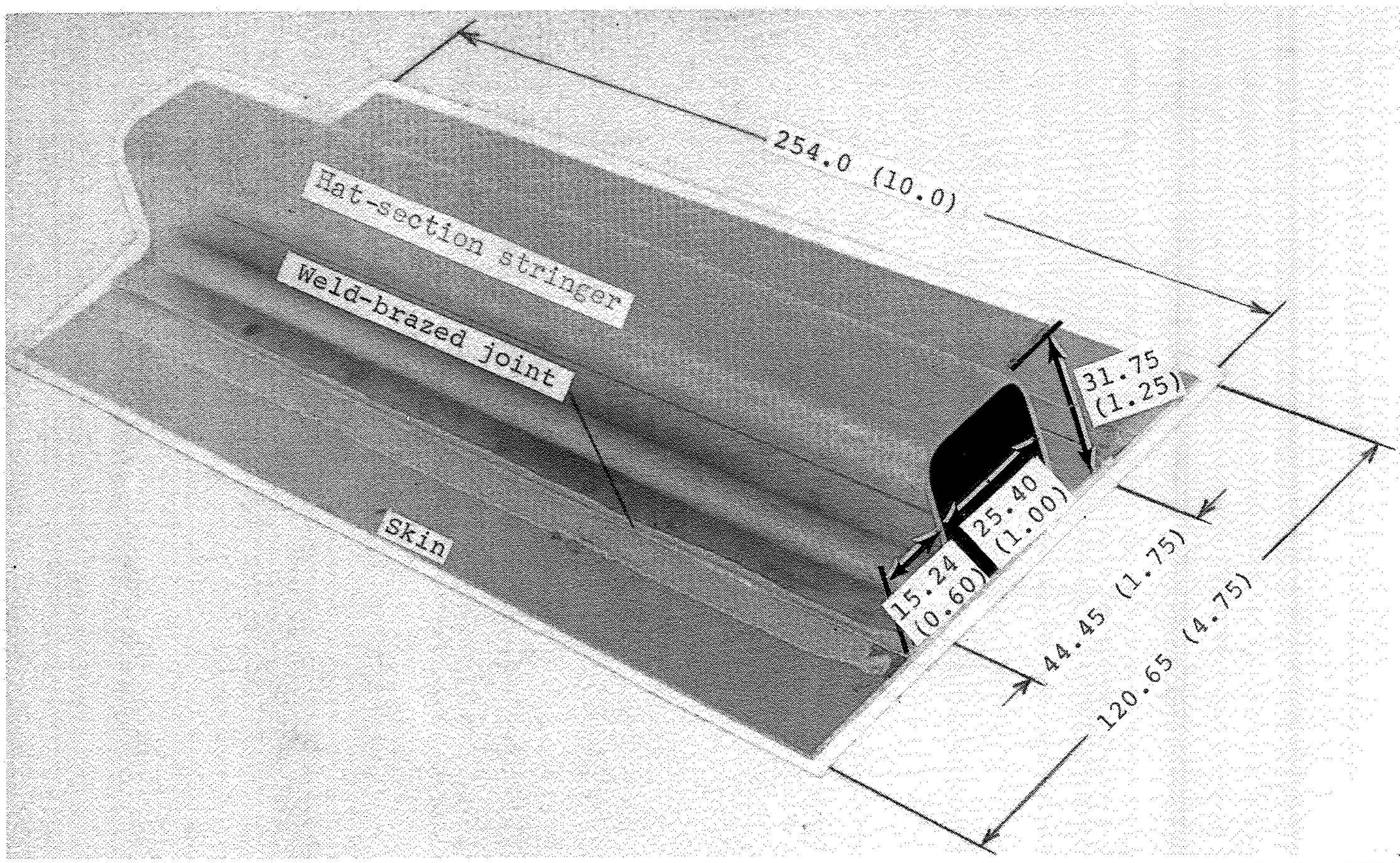

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Figure 6.- Weld-brazed skin-stringer panel. Dimensions are given in millimeters (inches).

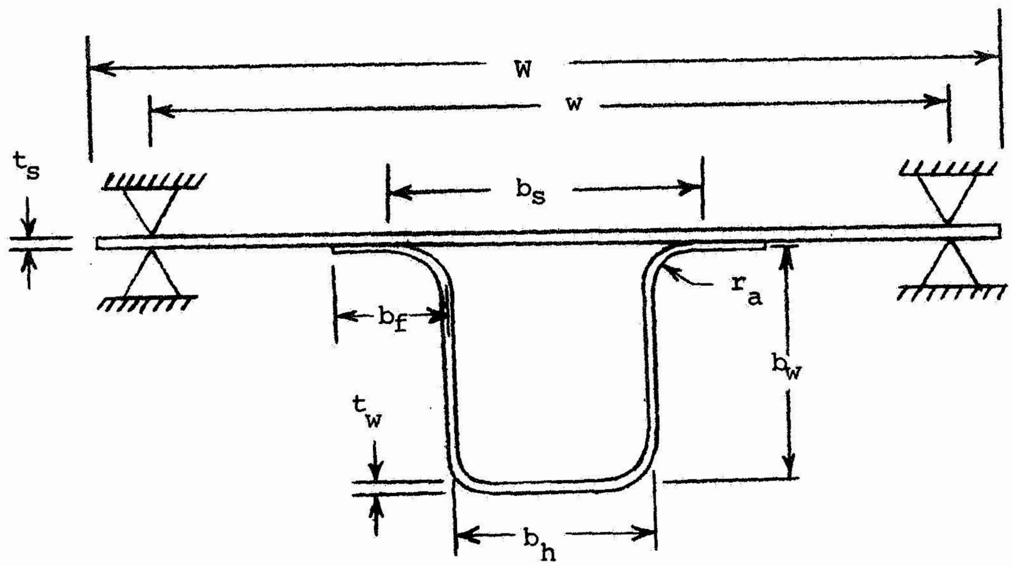

Figure 7.- Cross section of skin-stringer panel.

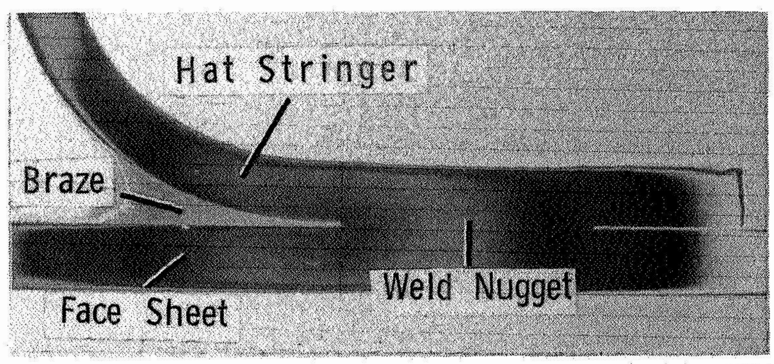

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Figure 8.- Weld-brazed joint.

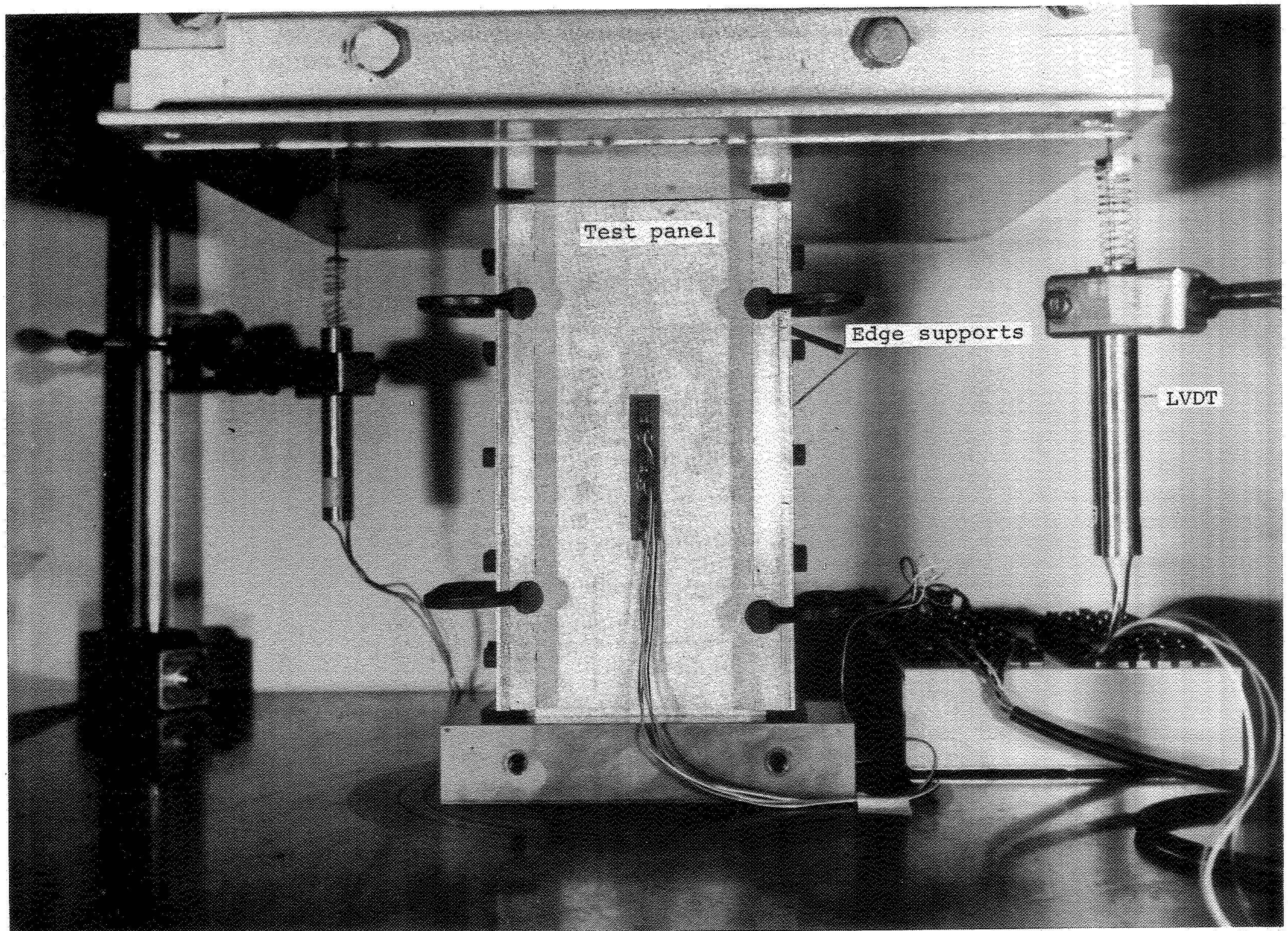

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Figure 9.- Test setup for skin-stringer panels.

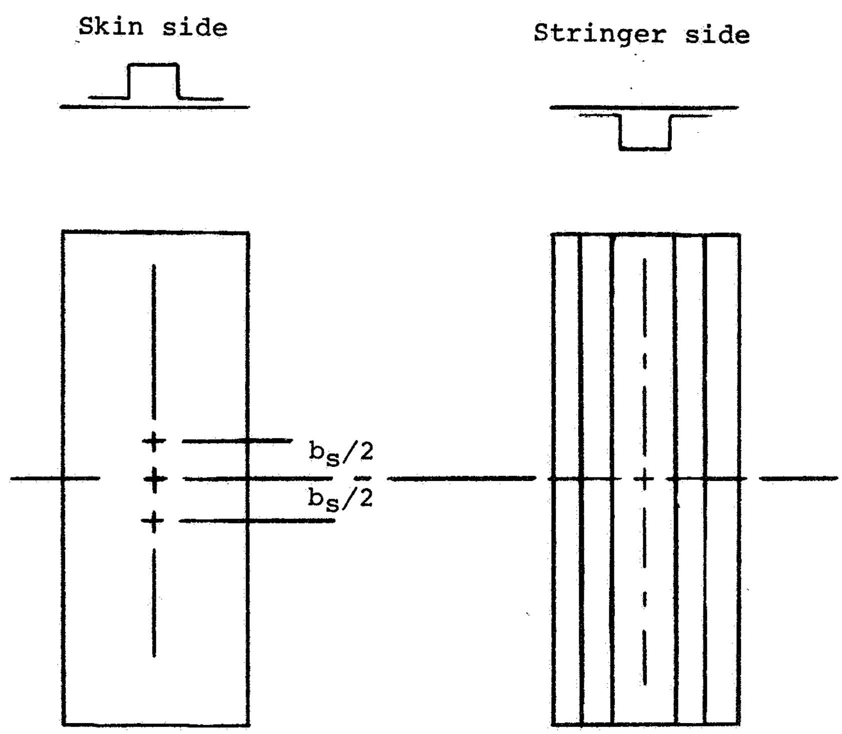

Figure 10.- Location of strain gages used in ambient-temperature test of skin-stringer panels.

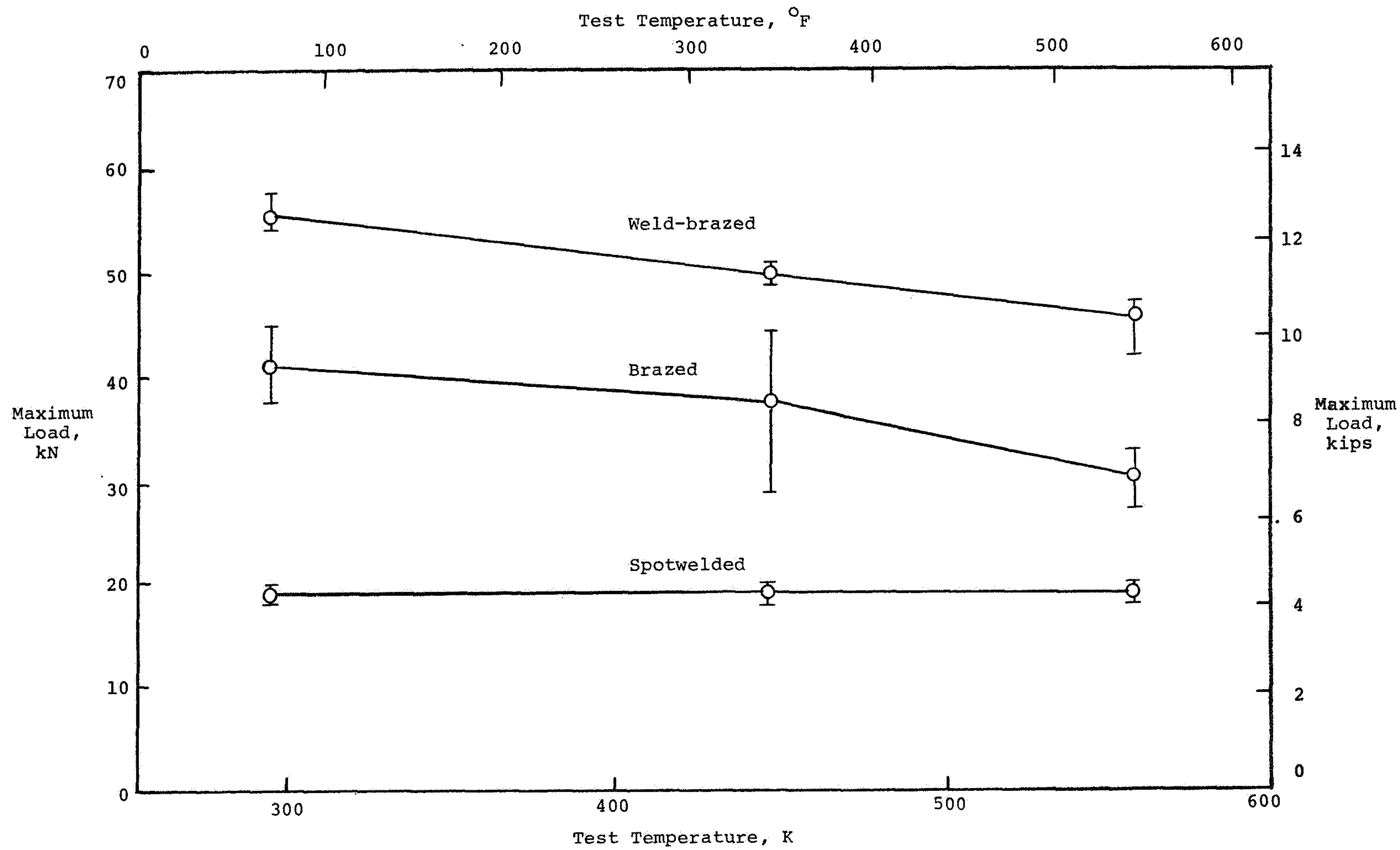

Figure 11.- Effect of temperature on tensile-shear strength of single-overlap specimens.

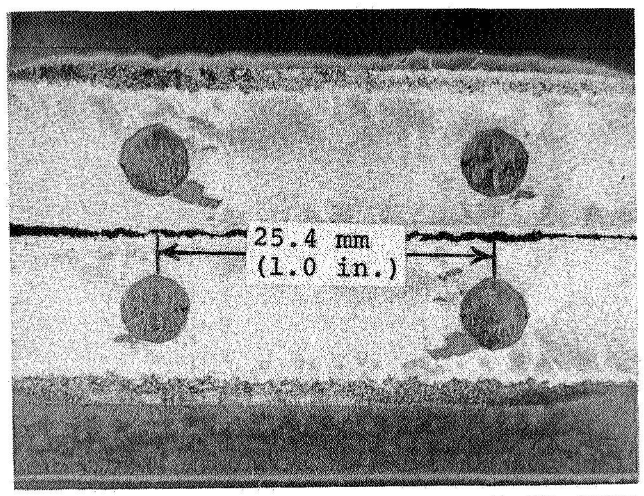

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Figure 12.- Typical shear failure of weld-brazed joint.

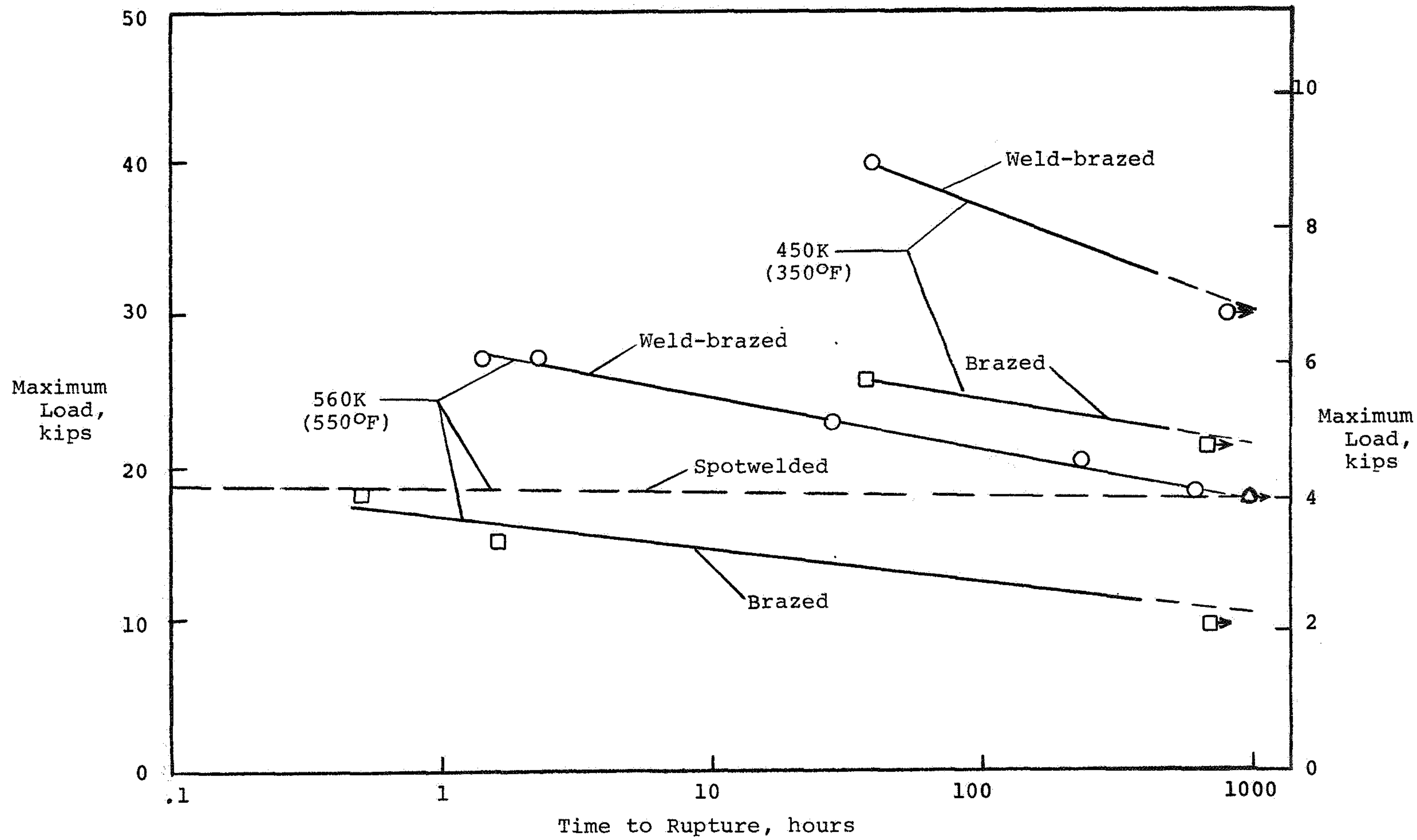


Figure 13.- Stress rupture of single-overlap specimens.

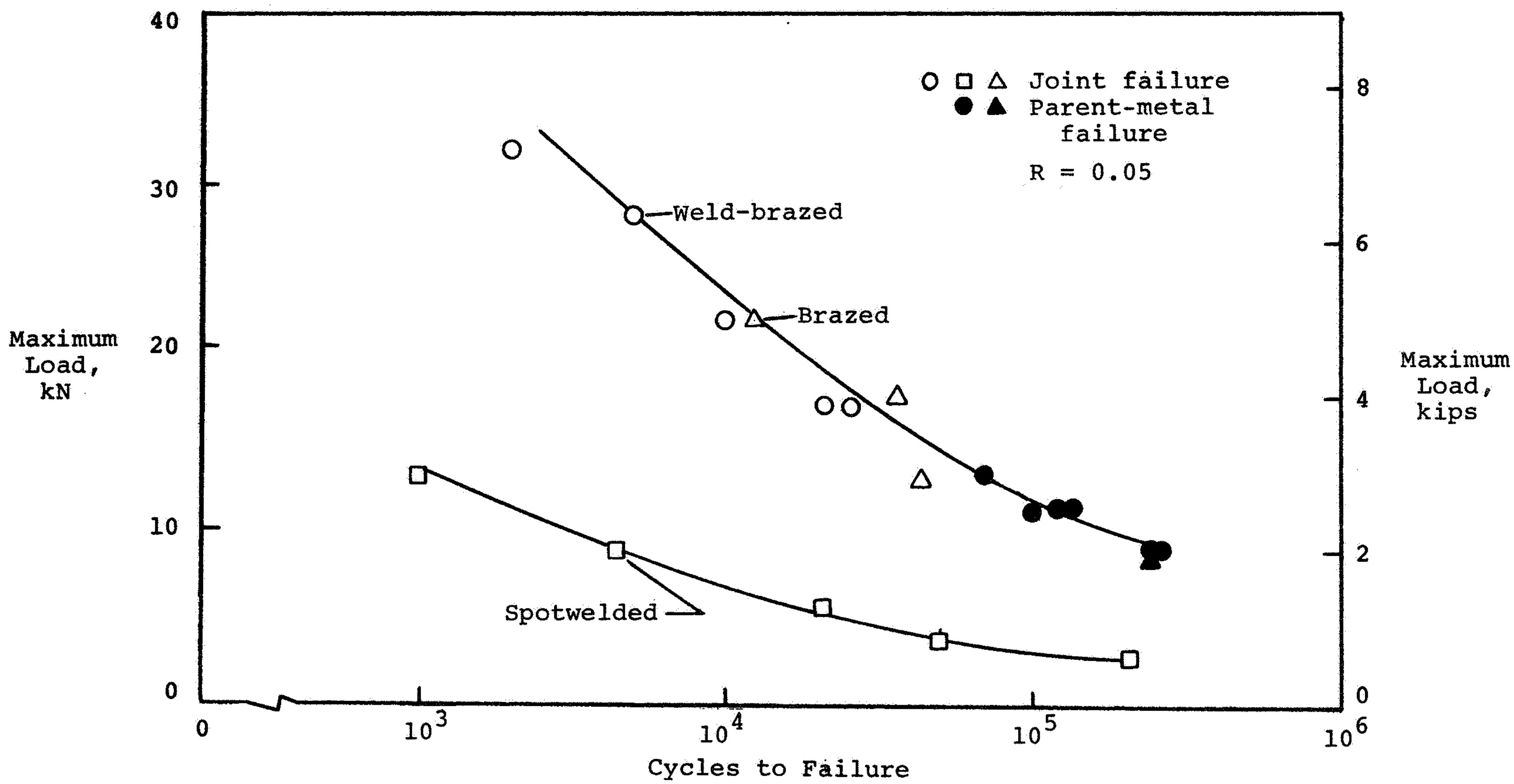


Figure 14.- Results of ambient-temperature fatigue tests on single-overlap specimens.

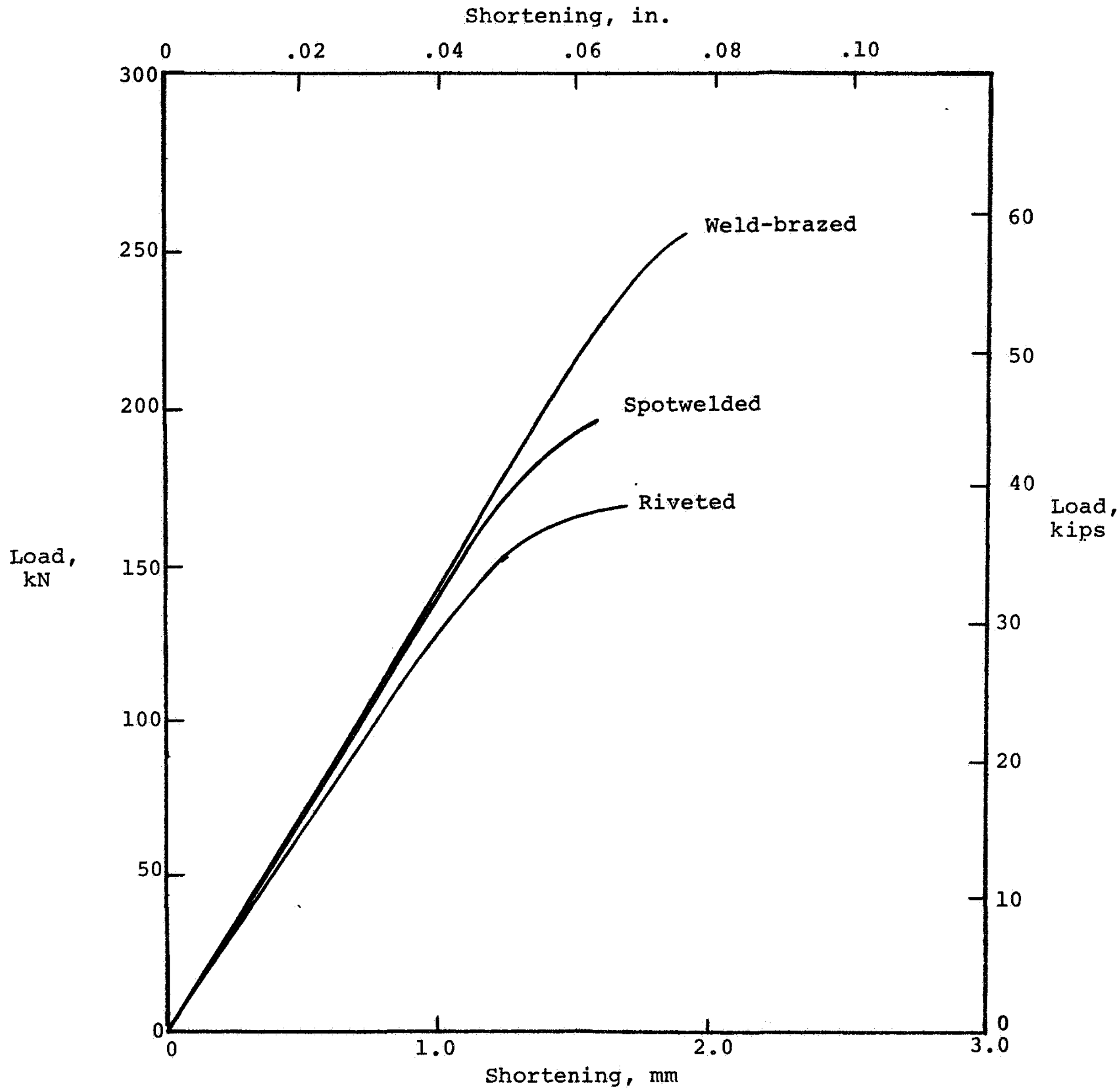
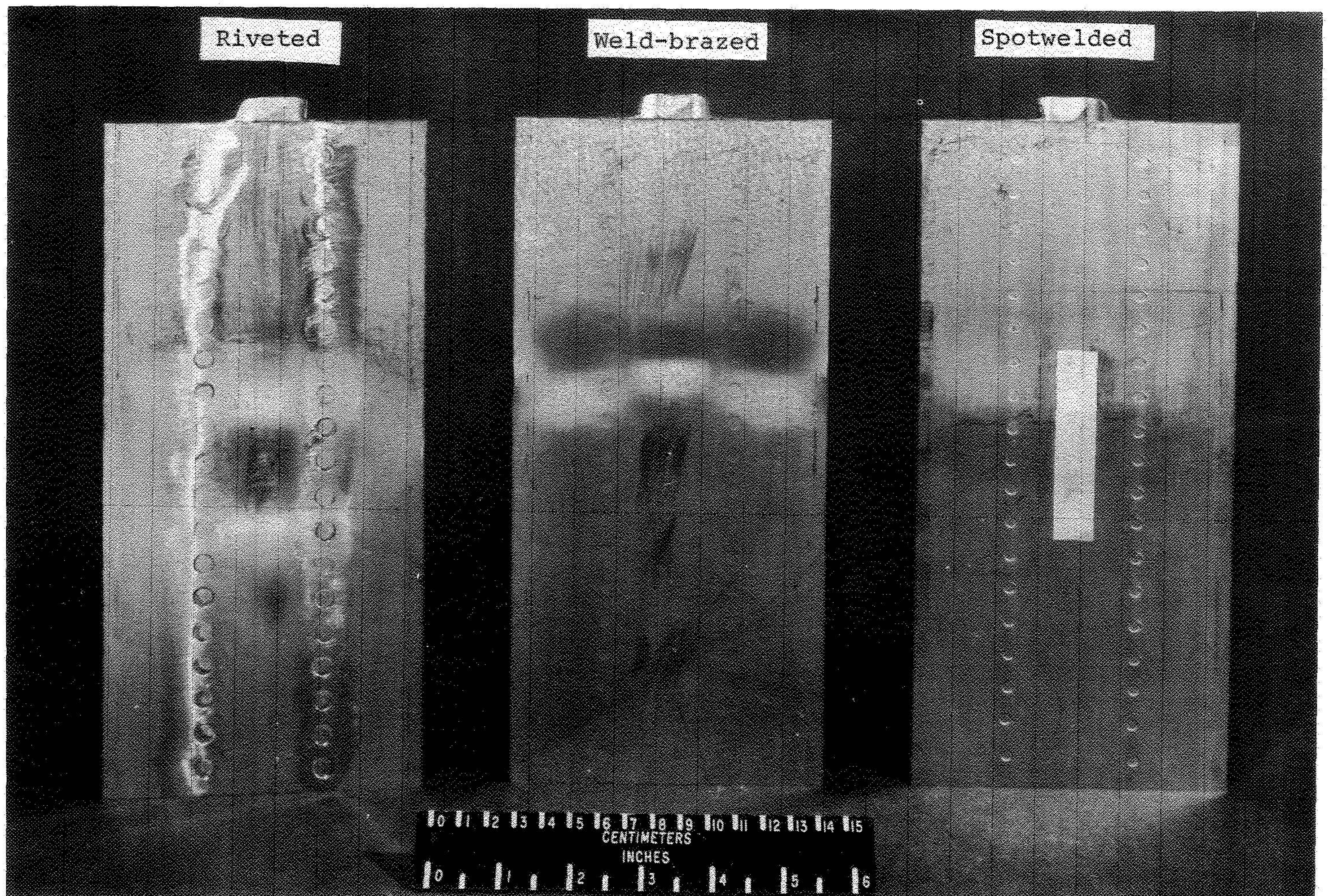


Figure 15.- Typical ambient-temperature load-shortening curves for skin-stringer panels.



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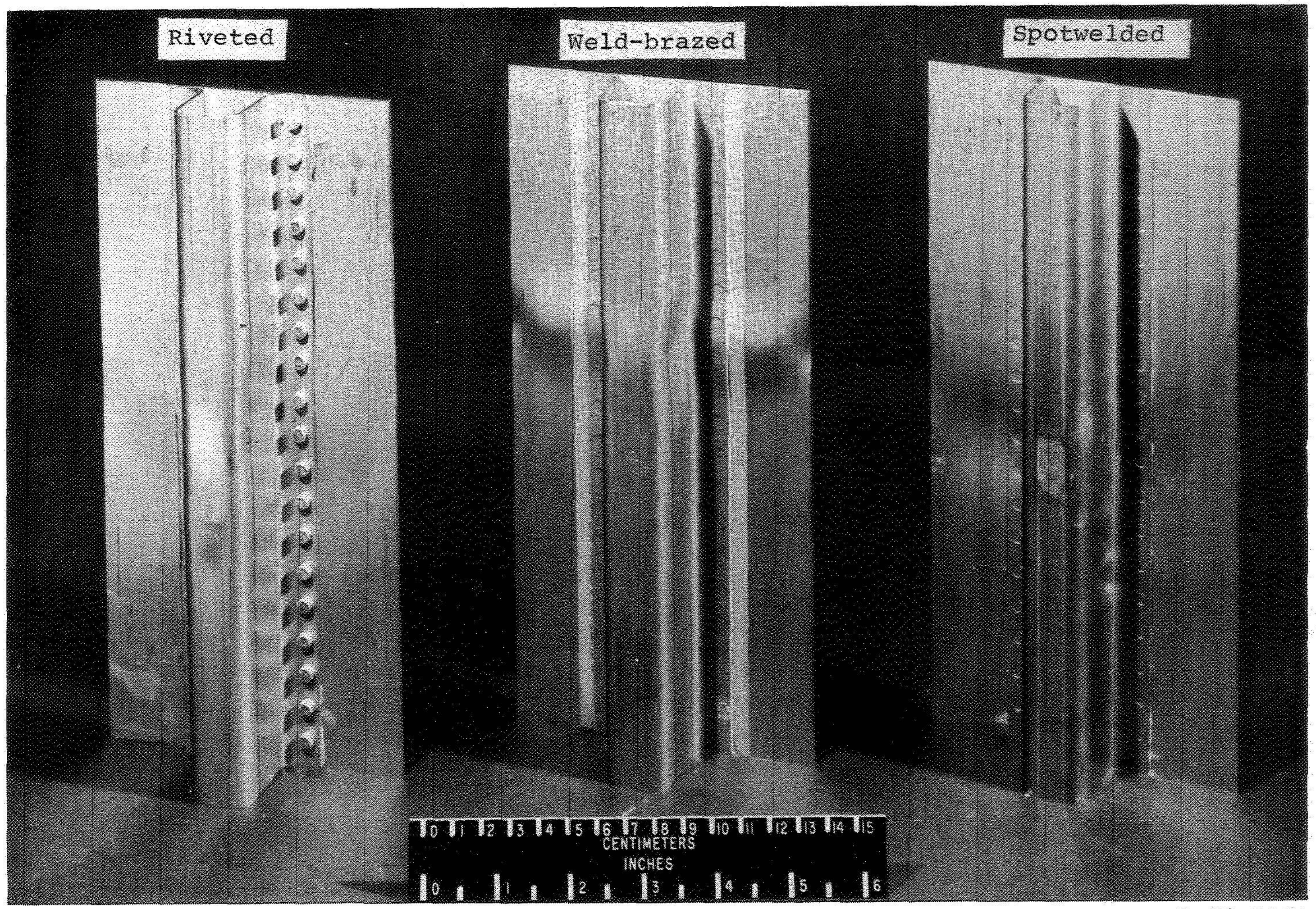
(a) Skin side.

Figure 16.- Typical failures of skin-stringer panels.



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(b) Stringer side.

Figure 16.- Concluded.

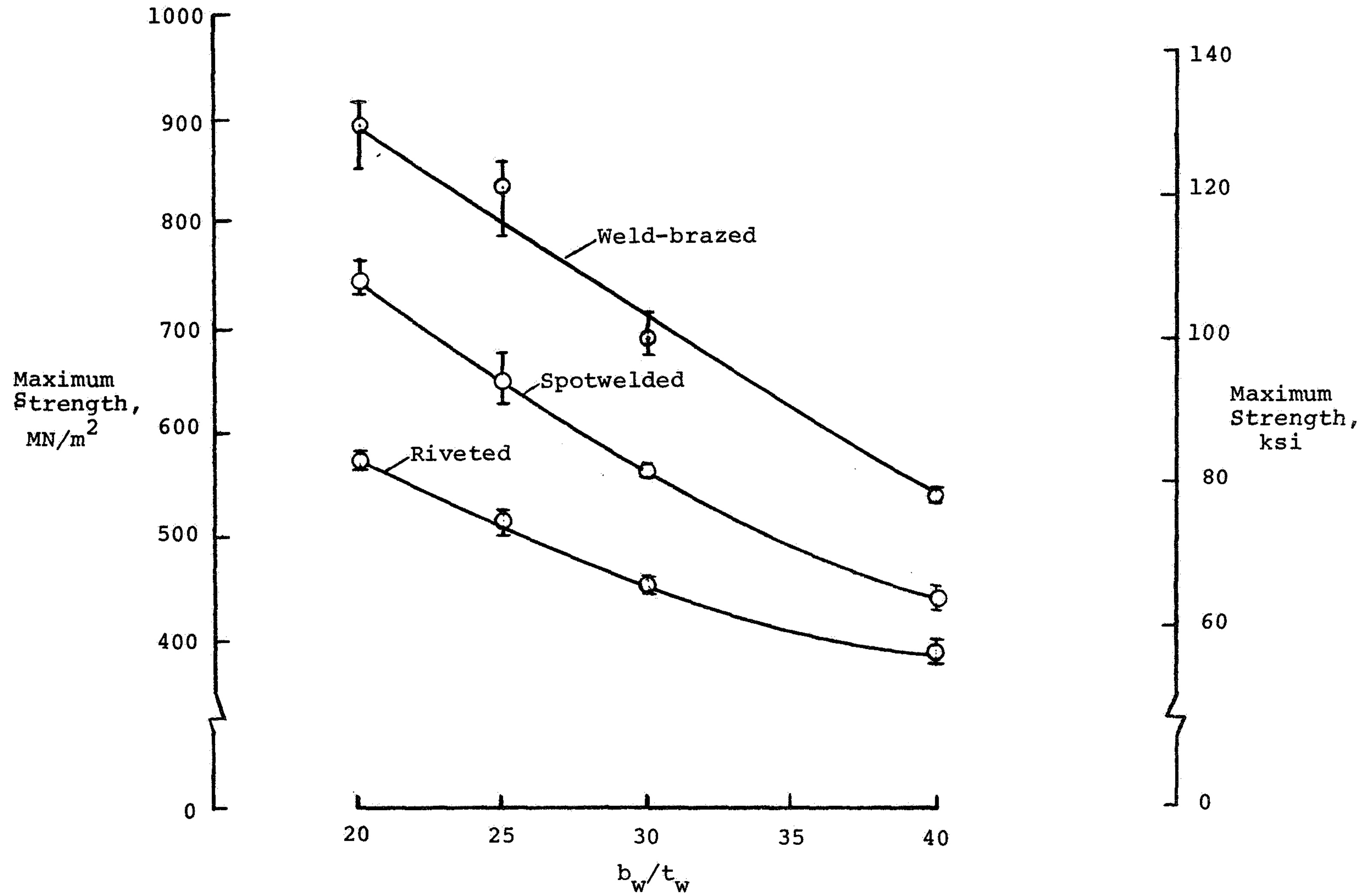

Figure 17.- Effect of b_w/t_w on maximum strength of skin-stringer panels.

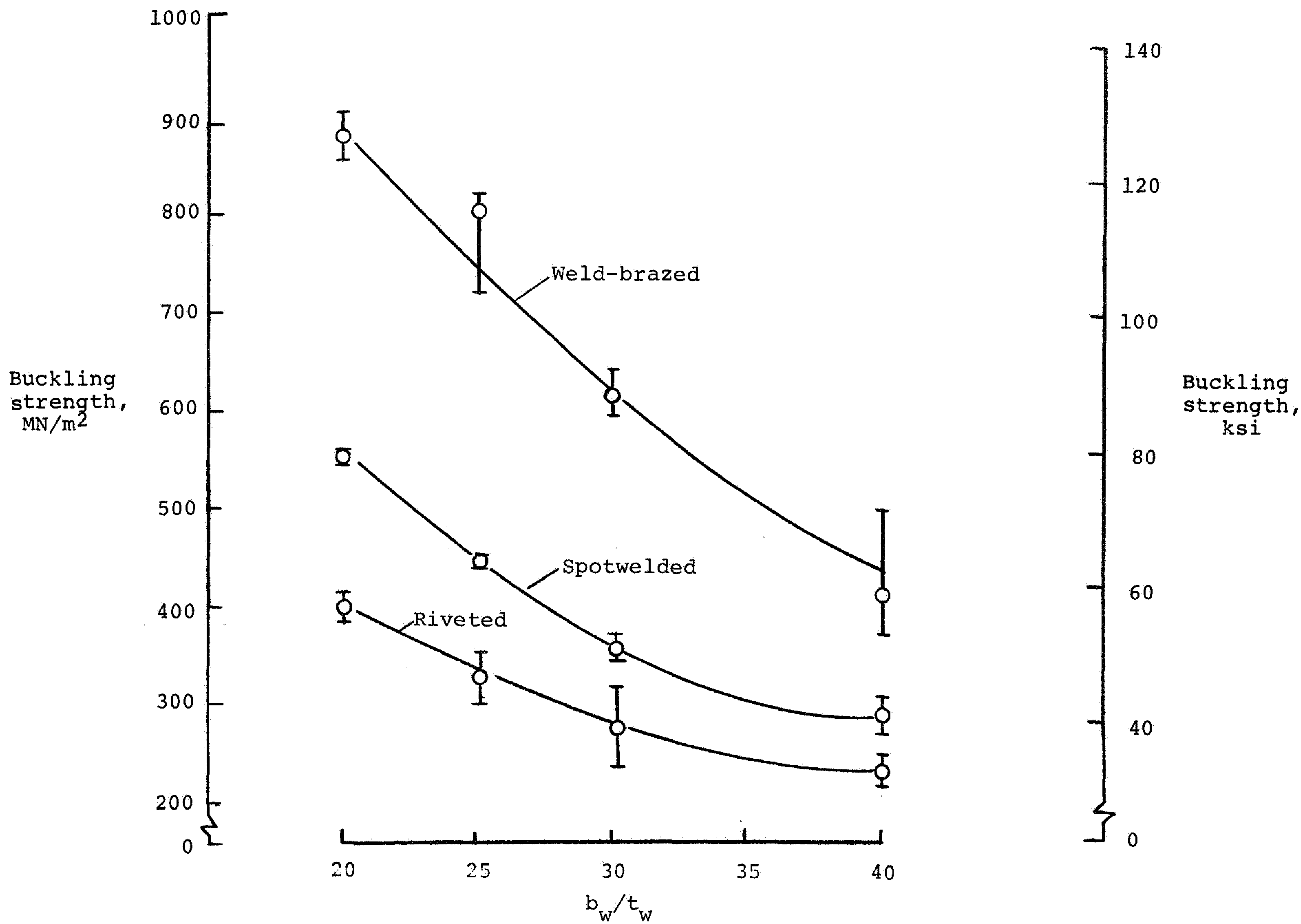

Figure 18.- Effect of b_W/t_W on buckling strength of skin-stringer panels.

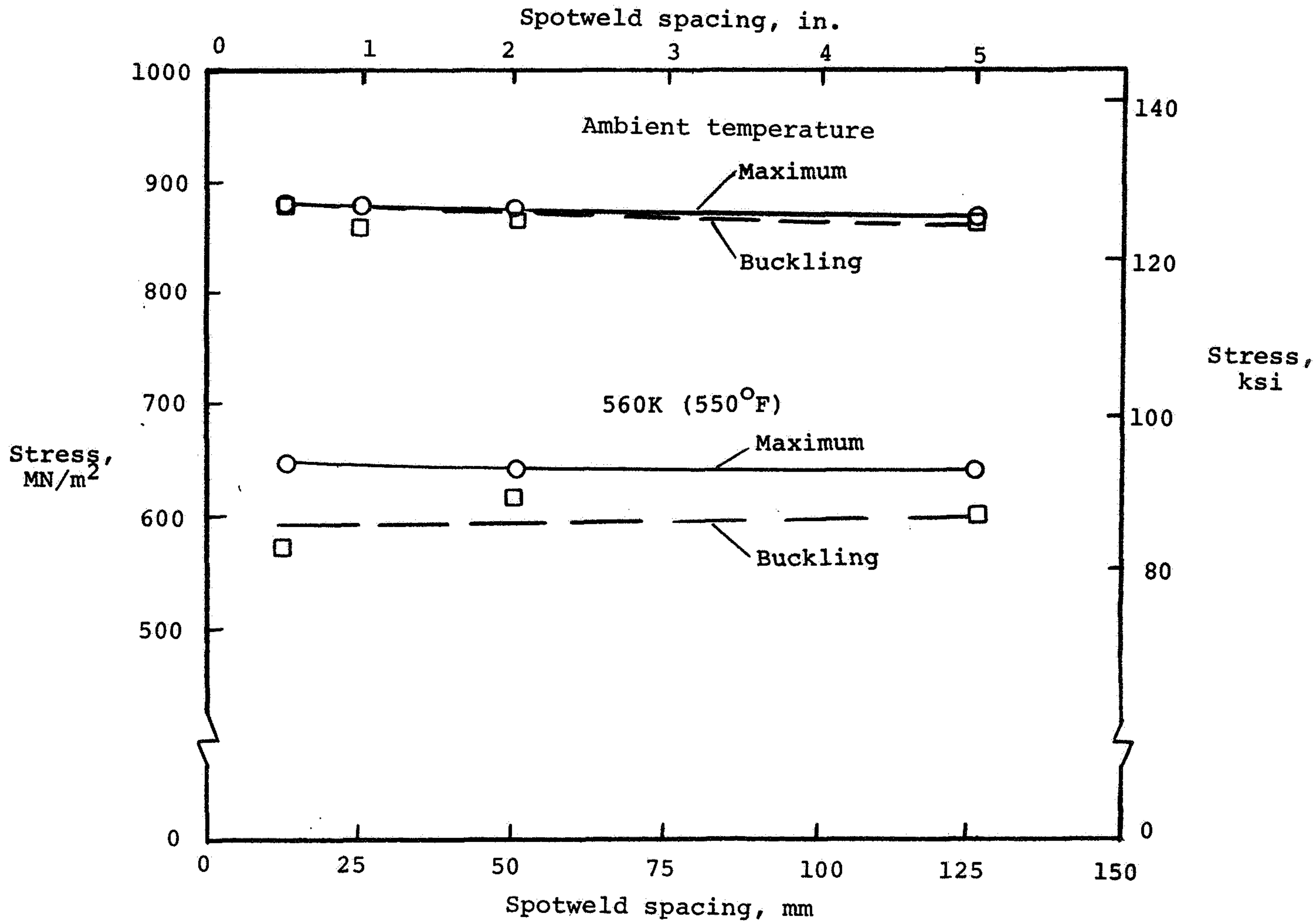

Figure 19.- Effect of spotweld spacing on maximum strength and buckling strength of weld-brazed panels.

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